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## Comfort, Acceptance, and Preferences: The Designing of a Human-Robot Workstation that Puts the Human First

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COMFORT, ACCEPTANCE, AND PREFERENCES: THE DESIGNING OF A  
HUMAN-ROBOT WORKSTATION THAT PUTS THE HUMAN FIRST

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A Thesis  
Presented to  
the Graduate School of  
Clemson University

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In Partial Fulfillment  
of the Requirements for the Degree  
Master of Science  
Mechanical Engineering

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by  
Jassmyn McQuillen  
May 2021

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## ABSTRACT

The purely manual versions of manufacturing are becoming less common, and automation is increasing. With mass production moving towards mass customization this change is inevitable. However, a future of automation does not mean that operators are going to be replaced. In fact, it means that operators' jobs are about to become more meaningful and value adding for themselves and the company. Soon majority of the jobs where operators do the repetitive mindless task of a robot will be gone. It is time for Human-Robot Collaboration (HRC) to advance the assembly process to the next level. Human-robot teams will be formed to combine their individual strengths and compensate for their individual weaknesses.

The success of human-robot collaboration heavily depends on the operator's acceptance of the robot. Unfortunately, operators are worried about robots taking their jobs, diminishing their self-worth, and putting them in danger. To mitigate these concerns the objective of this thesis is to model the design requirements of a human-robot collaborative assembly station that appeals to operator comfort and acceptance while still supporting the needs of production. A combination of fulfilling requirements, providing the operator with a better understanding of the robot's capabilities, and providing the operator with limited control could lead to an improved interaction between operators and robots.

Operator feedback was obtained from professionals in industry through surveys and structured interviews. Then the Quality Function Deployment (QFD) tool was used to translate the vague operator requirements captured in the survey responses and interviews into product-relevant parameters that designers and engineers can apply. The nine operator

requirements derived for working with robots are safety, dependability, value-adding, controllability, helpfulness, easy to communicate with, teachable, easy to fix, and enjoyable to work with.

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## CHAPTER ONE INTRODUCTION

With the manufacturing industry moving from mass production to mass customization manual ways of production are no longer efficient enough to handle the challenges facing the industry [1]. There is also a rise in availability/usability of digital hardware and software, along with vastly decreasing cost. Sensors are cheap and machine learning is just a Udacity course away from any engineer. Because of the easy access to these tools and devices the use of digital technology has increased, and the manufacturing industry is slowly moving towards Industry 4.0. The only thing left to do is provide guidance on how this digital hardware and software should be integrated into an effective system. Factories will not be fully automated unless a big shift happens, so the question is, how do people need to work with digital technologies? One effort in this area is collaborative robots [2]. The concept of light-weight collaborative industrial robots that could work with humans to improve production was first introduced by Peshkin and Colgate thirty years ago in 1991 [3].

The goal for human robot interaction (HRI) is to be safe, easy, flexible, and efficient. With the right safety devices, collaborative robots or *cobots* create opportunities to merge the versatility and manual skills of operators with the load capacity and process repetitiveness of a robot [4]. Many operators have misconceived the goal of cobots. Operators fear that cobots have been designed to take humans out of the job when in reality, cobots are there to make sure operators have more value-added tasks [5]. Instead of repetitive tasks operators should have greater engagement and leverage the ability to

dynamically sense and adapt to variation. In fact, cobots help to provide a role for operators in this new digital age. However, before operators and robots can form an efficient team there are concerns about human-robot collaboration (HRC) that must be addressed.

From a company's perspective HRC concerns are centered around the acceptance of operators and HRC's impact on safety, quality, and reliability. There are also issues deciding how to assign tasks and determining if operators will have the skills required to work alongside the robot. Fortunately, as the company determines what skill sets are needed for production, educational programs for future operators are created. Companies have even partnered with technical colleges to create educational programs. To see a benefit in HRC, companies need to know that safety, quality, and reliability concerns are not an issue. HRC should be cost efficient, provide ergonomic improvements, and promote successful collaboration between operators and robots.

Operator safety should always be a priority; and therefore, safety is one of the main concerns of HRC. Instead of keeping robots and operators separate, HRC puts them together in one workspace collaboratively working on the same tasks [6]. Operators and robots sharing a workspace could create potential opportunities for operators to get injured. One of the key contributions to operator injuries is a lack of situational awareness. Situational awareness is the ability of the operator to know what is going on around them. Kaber and Endsley highlight two types of problems associated with a lack of situational awareness [7]. The two types of problems include failure to detect a problem and failure to understand a problem. Failure to detect a problem and failure to understand a problem were hypothesized to occur due to three major mechanisms in a manufacturing setting: changes

in vigilance and complacency associated with monitoring, allowing the operator to have a passive role instead of being more involved with the robot, and changes in the quality or form of feedback received from the robot [7]. It is important that engineers consider these factors so that HRC can be designed to maximize situational awareness.

Efficient task distribution between the operator and the robot is crucial. When it is done incorrectly it can cause excessive cost, unevenness in workflow, dissatisfaction of the operator, quality issues, long cycle times, and issues with resource distribution. Tasks are also distributed to improve ergonomics. Any tasks that involve heavy lifting or repetitive tasks should be assigned to the robot [5]. This is a way of conducting skill-based task distribution, which is assigning tasks based on the strengths of the robot and the human. Another way to look at skill-based task distribution is determining what group of operators should be assigned a task. In manufacturing there are going to be operators that do not have any experience with robotics and operators that have years of experience interacting with robots. At first, the majority of the operators are most likely going to be inexperienced when it comes to working with robots. This lack of experience is important to consider so that tasks that require robotic knowledge can be grouped together in a smaller number of stations [8]. Another way to overcome the lack of robotic knowledge is by making the interface for working with robots easy to use.

HRC systems must have a fluid interaction. In this context fluency is defined as the ability of the operator and the robot to work together in a smooth and natural manner. The two should work as a team and achieve a synchronized interaction. Hoffman determined that fluency can be split into two categories, subjective and objective [9]. According to

Hoffman, subjective fluency varies depending on how the interaction between the operator and the robot is perceived and is affected by the level of trust the operator puts into the robot, the perceived contribution of the robot, how the robot exhibits positive teammate traits, and the operator's belief that the robot is committed to the team. Objective fluency depends on how many tasks are done simultaneously, how long the operator is idle, how long the robot is idle, and the robot's functional delay [10]. The robot's functional delay is the amount of time it takes to process before performing an action. With better fluency comes shorter cycle times or fewer stations.

### Methods for Implementing Successful HRC

Table 1: References for Human-Robot Collaboration

Reference	Topic	Approach	Purpose
Ahmed et al.	Reliability and Quality Control	Quantitative Analysis	Improve quality and consistency
Baskaran et al.	Evaluating Various Scenarios	Siemens Process Simulate	Test different solutions
Bilberg et al.	Implementing HRC	Simulation-based Digital Twin	Seamless integration
Dalle Mura et al.	Task Assignment	Genetic Algorithm	Design assembly lines
Gopinath et al.	Situational and Mode Awareness	Case Study Analysis	Improve safety
Grahn et al.	Advantages of Large Robots	Evaluation Scheme	Improve ergonomics
Hoffman	Fluency	Amazon's Mechanical Turk Platform	Create a tool to evaluate fluency
Kousi et al.	Ease of Use	Augmented Reality	Keep humans in the execution loop
Malik et al.	Skill-based Task Distribution	Design for Assembly	Improve task allocation
Mateus et al.	Structured Design Methodologies	Four Block Method	Standardize approach for designing HRC
Unhellkar et al.	Human Motion Prediction	Human-aware Robotic System	Improve safety and fluency
Wang et al.	Human Motion Analysis	Deep Learning	Improve safety and efficiency

Researchers have developed different methods for creating successful HRC.

Ahmed et al. used a quantitative analysis approach to reduce variation, inaccuracy, and defects in order to improve quality and reliability in HRC [11]. The methodology used was comprised of four steps, the first of which starts with identification of the factors that affect the quality and reliability of the product. Then the second step determines what characteristics the robot and the human have that contribute to the identified quality and reliability issue. This is followed by a third step that studies the correlation and regression

analysis modeling of inputs and output factors. Lastly, the fourth step conducts a sensitivity analysis and implements the control mechanism [11].

Baskaran used Siemens Process Simulate to improve planning and decision making for HRC [12]. Siemens Process Simulate has the ability to virtually validate manufacturing concepts. The software was used to integrate the ability to test and simulate different HRC solutions without having to physically move things around. With the need for mass customization comes the need for a large variety of components. In order to keep up with the variety of components manufacturing has to be flexible and innovative. To be flexible and innovative without wasting money on failed attempts one must embrace the digital manufacturing revolution and its ability to provide validation of manufacturing processes [13]. Testing alternatives in the digital world also allows for detailed planning before becoming fully invested.

Bilberg was able to control robots in real time, delegate tasks to humans and robots based on skill level, and create a sequence of tasks with a robot program through the use of digital twins [14]. A digital twin is a virtual representation that serves as a real-time digital counterpart to a physical object or process [15]. Bilberg was able to accomplish real time control, dynamic skill-based tasks distribution, task sequencing, and robot programming with the use of an Event-driven Simulation-based digital twin. The work environment that is needed for HRC is complex and dynamic. In order to offer high product variability these systems need to be able to continuously extend and adapt. Validation also needs to be quick and efficient during design, development, and operation. New design approaches need to be able to accommodate the high complexity, safety, and efficiency needs of HRC [14].



These needs can be met with the use of a digital twin. The system developed by Bilberg is composed of four modules [14]. One module is tasked with decomposing the product assembly into tasks that will be evaluated based on physical properties and assembly characteristics. The second module focuses on simulating each task and estimating cycle times. During the second module key-positions are defined in order to help with future robot programming. The third module receives the data from the simulator and begins to assign the appropriate resources for balanced production between the robot and the operator. The program for the robot is also generated. Then the fourth module sends the robot program to the robot and the operator task instructions to the screen in front of the operator [14].

Dalle Mura developed a method to minimize assembly line cost, minimize the number of skilled operators needed in the assembly process, minimize the distribution of resources, and improve ergonomics with a genetic algorithm [8]. The Genetic Algorithm (GA) accomplished these goals by creating a chromosome structure that is formed by two sub-chromosomes in order to represent a feasible configuration of the assembly line [16], [17]. These sub-chromosomes are centered around task and human-robot interaction. The task sub-chromosome includes a list of assembly operations in order of execution. The human-robot sub-chromosome contains the operators and robots assigned to the operation. Then the tool proceeds to determine optimal solutions for problems on a large scale [8].

Gopinath developed an understanding of what characteristics and hazards are associated with human-robot interaction and designed a solution to minimize those risks through case study analysis in order to improve safety [18]. It was identified within the

paper that situational and mode awareness is important to ensure operator safety during HRC. The data was collected by constructing interviews and a literature review on human-automation interaction. Then while analyzing the case study observations of the risk assessment processes were documented [19]. The observations were focused on the delegation of the tasks, the workspace, and the mode of operation. The risk reduction measures were evaluated in how they support safety, when they support safety, and where they report safety [18]. It was through the evaluation of these components that Gopinath realized situational awareness was one of the key factors to ensuring safety.

Grahn decided to focus on improving ergonomics by reducing the amount of lifting that operators have to do as well as the need for lifting tools with the help of an evaluation scheme [20]. The evaluation scheme focuses on role assignment, acceptability, context, level of automation, assembly sequences, and set-up time while implementing and evaluating collaborative work cells. With the help of the evaluation scheme the engineer can determine what is needed to improve implementation. The evaluation scheme was used to evaluate an approach that uses large anthropomorphic robots [21], [20]. The goal was to demonstrate how ergonomics can be improved through the use of large anthropomorphic robots. It was identified that more parameters need to be added to the evaluation scheme to make it more effective in guiding the implementation of HRC [20].

In order to design better human-robot teams, Hoffman evaluated the level of fluency between humans and robots within shared locations with Amazon's Mechanical Turk as a research platform [9]. The idea was that if fluency could be evaluated and improved then it would lead to a better designed HRC. Amazon's Mechanical Turk allows

for individuals and businesses to outsource their processes and jobs to a distributed set of participants who can perform tasks virtually. First a literature review was conducted in which it was determined that there is subjective fluency and objective fluency. Then a human-robot collaborative scenario simulator was created to conduct an online study to validate their findings. There were some issues with this set up because fluency perceived from an outside observer can differ from how a participant would perceive fluency within the system. Even though Hoffman was able to create parameters to evaluate fluency there are still other aspects of fluency that were not considered and need to be addressed [9].

Kousi et al. created an interface that would allow operators to interact with robots without needing to be experts on robots by using an Augmented Reality (AR) based approach [22]. With Augmented Reality based software and HoloLens AR glasses Kousi was able to improve human robot interaction [22]. A method was created with this AR system to keep operators in the execution loop and make it so that operators do not need expertise in robotics to work with them. The operators could directly instruct the robot, receive real time information, and provide feedback on their execution status in real time. The method requires the use of a digital twin of the production environment and a station controller that sends the scheduled tasks to the human and the robot while monitoring the execution status through the central execution system [22]. Having this AR device also allows operators to quickly re-program the robot from any location. The system that connects the AR tools to the robot controller are generic enough that they can work with a variety of assembly processes regardless of the layout or robot model used [22].

In order to lower changeover time and improve work-load balance, Malik developed a task distribution method based off of Boothroyd's Design for Assembly (DFA) guidelines [5]. Since Boothroyd did research on the use of robots for assembly that identified which factors make it easier for robotic assembly the DFA based method approach was developed in order to develop skill-based task distribution [23], [5]. The attributes that affect human-robot collaboration include grasping ability of parts and components, feeding mechanism, mounting and insertion, fastening and safety [5]. Many of these factors are already analyzed during a regular DFA analysis. Therefore, as long as the part is designed for assembly, a DFA based method for skill-based task distribution works well. The DFA based method process starts by decomposing the product into parts that are defined by assembly task. Then analysis of the part is done based on characteristics and how the part is fed into the assembly. Next, the process is analyzed based on how the part is mounted and joined. Lastly, the workspace is considered for safety, assembly precedent constraints, and task time. Each task is then assigned an automation potential ranking. Additionally, there is a risk analysis component that determines if the assigned tasks could produce a potential safety hazard [5].

Mateus developed the four-block method because he felt that there should be a generic methodology for implementing close HRC that would help with work allocation, distribution of work, and corresponding layout constraints [24]. This method addresses some of the fundamental aspects of HRC workstations including, safety, ergonomics, and time performance. The tool generates alternative HRC assembly sequences based on work allocation, work distribution, and workspace layout. The first block in the method takes

information about the product and the assembly sequence constraints from the CAD models. Then this information goes into the second block where the tasks are broken down to determine the functional requirements. Once these requirements are determined the third block determines resource capability and safe collaboration options. In the fourth and final block all of the information is combined to generate and analyze possible HRC assembly sequences [24].

Unhelkar improved the safety and fluency of HRC through a human-aware robotic system called CobotSAM [25]. It was created to help mobile robots in HRC execute efficient and safe motions. The program has the ability to improve safety and fluency. This was proven by the fact that the case study resulted in fewer safety stops and improved task efficiency. The CobotSAM system was created with five components. This includes the robot, the safety system, human motion prediction, trajectory planning and execution, and a way to communicate between the subsystems [25].

Wang improved safety and fluency with a Deep Learning (DL) approach [26]. Deep learning is an artificial intelligence function that processes data and creates patterns for use in decision making. DL has been known to outperform human experts in recognition or strategy-related task [27]. During the case study DL was capable of being 96.6% accurate while other traditional machine learning methods are usually only 70-80% accurate[28], [29]. The DL based modified program, AlexNet, was used to improve efficiency and safety in HRC through human motion analysis. AlexNet allows for motion recognition and context awareness. With context awareness the robot knows when to pass what tools or parts to the operator. The program tracks the operator's motion, identifies the context of

collaboration, and predicts what the operator will do to accomplish a task and what the robot needs to do to help.

Each previously mentioned researcher developed a different method to handle respective issues with HRC. However, the overall goals were the same, to improve HRC and to make it more efficient, safe, and user-friendly. The researchers wanted to ensure their system had the best characteristics to produce close-to-optimal performance while making things easier for the operator.

### **An Alternative Method for Implementing Successful HRC**

**The objective of this thesis was to model the design requirements of a human-robot collaborative assembly station that maximizes human comfort and acceptance while still supporting the needs of production.** The idea of human-based preferences (*i.e.*, which human-controlled variables have a significant effect on station productivity) was explored. A survey was designed to present a superset of potential human variables to a group of users with knowledge of assembly processes. The results were used to identify a limited set of significant characteristics. Using these as design variables, design requirements for a human-robot collaboration workstation was determined along with an approach for user-controlled preferences to allow for personalization. To validate these design requirements, follow-up interview questions were designed. With a human focused design, the aim was to treat the operators like the customers and develop a method to improve operator comfort with the belief that it could lead to improved efficiency. For the purpose of this thesis comfort is defined as a feeling of well-being, relief or satisfaction

that is caused by the approach a robot takes to complete shared tasks in a collaborative setting. [30].

The formulation of requirements was accomplished with the help of Lean Six Sigma tools [31]. Lean Six Sigma is a process improvement methodology designed to eliminate problems, remove waste and inefficiency, and improve working conditions to provide a better response to customers' or in this case operators' needs. It combines the tools methods and principles of Lean and Six Sigma into one powerful methodology for making improvements. The tools used from this Lean Six Sigma concept include Voice of Customer (VOC), Affinity Diagrams, Critical to Quality (CTQ), Kano, and Quality Function Deployment (QFD) all of which will be further exemplified in Chapter four.

Currently in HRC research the robot is designed to sense and adapt to the operator over time. While this can be effective, such a method does not help the human understand the robot's intentions. When the operator can set their own preferences for collaboration, the operator has the opportunity to understand what the robot is capable of and how the robot will interact with them. Ideally, being able to set preferences would give the operator comfort knowing that the robot does not have complete control in the collaborative system. User-controlled preferences could also help the operator feel as if the robot is designed to work with them as a fellow team member. If the operator has a positive perception of the robot, the operator feels comfortable, and the robot knows the human's preferences the collaboration between the operator and the robot could be improved leading to a greater acceptance of robots. It is more likely that an operator will accept a robot if the operator feels that the robot's behavior and interaction style match their preferences, needs, and

abilities [32]. Acceptance should lead to better collaboration, and improved efficiency within the HRC workstation.

## **Motivation**

The success of human-robot collaboration heavily depends on the operator's acceptance of the robot [33], [34]. Unfortunately, due to operators' perception of robots there is a lack of acceptance. Operators are worried about robots taking their jobs, diminishing their self-worth, and putting them in danger [4], [34], [35]. The engineer must find a way to make the operator feel as if the robots are providing them jobs, giving them an enhanced sense of self-worth, and improving their safety [33]. A major mistake is when the engineers try to solve issues without involving the operator. The author attempts to avoid this mistake by treating operators like customers and asking them what they would require in a HRC workstation.

In order to improve acceptance, comfort within the system must be investigated. Since comfort is subjective, it is important to take varying user preferences into consideration while designing the workstation. The use of a survey helps to gather information and diverse set of participants can be pulled from the survey for an interview in order to capture the varying perceptions and preferences. This process would help determine a list of user-controlled preferences especially since operators can have different comfort levels even when they are completing the same task, with the same robot, in the same conditions [30]. Furthermore, the operator being able to set their own preferences for the workstation may provide an opportunity for the operator gain a better understanding of what the robot is capable. The opportunity could come in the form of an interactive profile



where the operator sets the preferences while the robot provides information about its capabilities. The exchange in information could lead the operator and the robot to developing a shared mental model, which could lead to a more natural interaction. Creating this shared mental model is one of the key challenges in human-robot interaction and it is essential to fostering closer collaboration [33], [36].

## **Overview**

This thesis consists of four parts. The background research, the operator feedback, the formulation of requirements, and implementing examples of the application of these requirements to a real-world industrial project. The goal was to mimic the process that a company should go through before implementing collaborative robots into their facility. The first step was to conduct background research to better understand the technology and how operators react to the implementation of collaborative robots. Then the next step was to conduct surveys and interviews within a company to determine the current opinion and feelings of operators towards robots. This also allows for a better understanding of what requirements are necessary to ensure that the operators have comfort and acceptance while working with robots. Then the feedback from the operators was converted to requirements that were applied to a real industry workstation concept. Once the requirements for the overall workstation were defined, the subsystem requirements were discussed. In conclusion, the company is well equipped to look for solutions that meet the requirements of the operator for an enjoyable human-robot experience and that can meet the needs of production.

## CHAPTER TWO

### BACKGROUND

The focus of this chapter is to inform the reader of the current state of human-robot collaboration in terms of comfort, acceptance, adaptability, preferences, and human-robot teams. These four areas are typically studied independently. When brought together they contain many of the components necessary for developing an efficient and enjoyable HRC experience for the operator.

One topic that is not discussed in this chapter is trust. This topic has been thoroughly explored and analyzed by many researchers [37]–[46]. Trust is important and related to HRC but rather than exploring trust further it is embodied through comfort and acceptance. In order to feel comfortable working with a robot the operator must trust the robot. N. Wang et al. pointed out that researchers have observed operators will trust a robot more if they understand the robot’s decision-making process [40]. The less an individual trusts a robot the more likely they are to intervene as the robot attempts to complete a task. Trust directly affects the willingness of people to accept robot-produced information, follow robots’ suggestions and benefit from advantages inherent to robotic systems [46]. By making improvements to ensure the operator accepts working with the robot and feels comfortable working with the robot the author is also ensuring the operator trusts the robot.

#### **Collaborative Systems**

It is important for companies to acknowledge that operators are vital to the success of environments where collaborative robots are deployed, as long as the cobots are used

correctly [47]. In the past, robots were simply used as tools for operators to use [48]. However, as robots have evolved, they have become increasingly capable of assisting operators as teammates that work together to accomplish joint tasks. Stark et al. stated that collaborative robots provide prospective and great solutions to complex hybrid assembly tasks [49]. This allows for tasks to be split between operators and robots based on their capabilities in order to leverage their unique advantages. The robots are also easily programmable and adaptable to different applications and can enhance productivity while saving costs [50]. Since cobots are designed to work collaboratively with operators instead of replacing them, emphasis has been placed on safety in their implementation [47], [51]. This focus on safety enables the cobot to physically interact with an operator in a shared workspace.

There are three levels of human-robot interaction: collaboration, cooperation, and coexistence. The term collaboration describes a process in which operators and robots work together on one part of the final product and are in direct contact with each other. Cooperation is when there is a division of labor where both operator and robot are responsible for certain portions of the tasks. Coexistence is when the operator and the robot work in the same area but do not share a common goal. Collaboration and cooperation are preferred over coexistence of operators and robots. Coexistence is referred to as the weakest form of human-robot interaction since it does not effectively combine the two skills of the operator and the robot [52].

The benefits of having operators and robots work together are that operators are more flexible and able to make decisions based on changes in production; whereas, robots

have more power and are better at repetition, accuracy, and integrating with data systems [52]. Using skill-based task distribution the two can work together effectively. Robots should be used for mindless, repetitive, sometimes strenuous, or even dangerous physical motions. Operators on the other hand should have more value adding positions where the operators can use their knowledge, experience, sophisticated decision making skills, and creativity [47]. Overall, human-robot interaction leads to increased flexibility and adaptability as well as improved ergonomics [52].

The operator and the robot have the ability to create a very efficient team. However, there are many issues that hold them back from being successful. For example, it is not possible to gain the benefits of collaborative systems without considering human factors. The lack of acceptance of robots among operators can cause a low prevalence of cobots in general. Then when cobots are used, an aversion to new technology can lead to erroneous operation which in turn can lead to a decrease in quality of work [52]. This thesis focuses on human comfort and acceptance, and the issues in human-robot collaboration that relate to these topics.

## **Acceptance**

Operator acceptance is crucial for the successful implementation of HRC in a company [34]. Acceptance has a huge impact on efficient and successful collaboration between operators and robots [13], [49]. In general, acceptance is a major research topic. For example, the way the operator's perceptions can affect their acceptance of robots in the workplace has been evaluated by researchers like Dalle Mura et al. [8]. The affect of operator's perceptions cause acceptance to be highly individualized and unstable, making

acceptance very subjective. The same robot within the same environment might lead to very different attitudes and behaviors across different operators. Acceptance is a complex psychological construct that cannot be achieved easily. Since the work between an operator and robot is mandatory, the indicators of acceptance are the operator's attitudes towards the robot instead of system use or use intentions [53]. Attitudes are the only way to accurately interpret the operator's actual level of satisfaction [50].

Bröhl et al. studied an acceptance model for human-robot cooperation [54]. He states that the one factor that predicts successful human-robot interaction is the acceptance of the robot by the operator. Only when a product covers operators' needs and expectations is that product perceived to be useful and hence accepted. To achieve acceptance the operator must perceive both usefulness and ease of use [13]. Perceived ease of use is how easy it seems to be to use a robot while perceived usefulness is the degree to which a person believes that using the robot will enhance his or her job performance. Job relevance is the most important variable to perceived usefulness followed by output quality. Job relevance refers to how important a robot is to the job-related tasks. Job relevance is also how well the robot's function relates to the requirements of the process. Output quality relates to the quality of the work that the robot performs, for example, if the robot conducts its work without making mistakes than that would be good output quality. Perceived ease of use is the degree to which the operator believes that working with the robot will be effortless. Bröhl et al. also suggests that different personalities make acceptance subjective. Personal characteristics such as self-efficacy, perceived enjoyment, robot anxiety, affinity towards

technology, robot-related experiences, and perceptions of external control can impact acceptance levels.

Lotz et al. also found job relevance and output quality to be important factors along with perception of external control and enjoyment [34]. Perception of external control relates to whether the operator has some control over the process and the robot. Enjoyment focuses on how much the operator enjoys working with the robot. Lotz et al. was able to identify a repeated occurrence of enjoyment as an important factor which implies the enjoyability of working with the robot can fundamentally shape the acceptance of the robot [34]. Lotz et al. found that attitudes towards the technology appear to be influenced by how HRC will impact the operator's daily work. The results were also diverse and individualized.

Wang et al. discusses how operator acceptance has a direct impact on the quality of the work completed by human-robot teams [49]. Measures to improve acceptance include developing the robot with a friendly and intuitive human-robot interface, designing different kinds of robots for diverse age groups, and improving the robot response to the operator's needs [49]. Their goals were to reduce the operators' idle time, improve fluency, and make the robot easy to use in order to improve acceptance. In this context, fluency is a high level of coordination that can lead to a well-synchronized mesh between operator and robot actions. Ideally, the operator does not have to wait for the robot and the robot does not get ahead of the operator.

Instead of pointing out solutions Meissner et al. focuses on identifying more factors that influence acceptance. Meissner et al. points out how individualized and unstable

acceptance is [50]. Figure 1 shows Meissner et al.'s findings. It identifies influencing factors on operators' HRC acceptance. Thoughts and feeling about HRC are the primary influencing factors. The perceived risks can lead to negative feelings while perceived benefits can lead to positive feelings. Object-related, subject-related, and context-related factors are secondary influencing factors and the dashed arrows implies that the factors could interact with each other. One primary reason why operators have negative attitudes toward HRC is because the operators do not have confidence that the executives will consider the operators' interests. This falls into the context-related context area of Figure 1. If operators are given a feeling of being appreciated and supported, they tend to have more confidence and positive feeling about the executives' decisions. This shows that it is important for operators to feel involved in the implementation process.

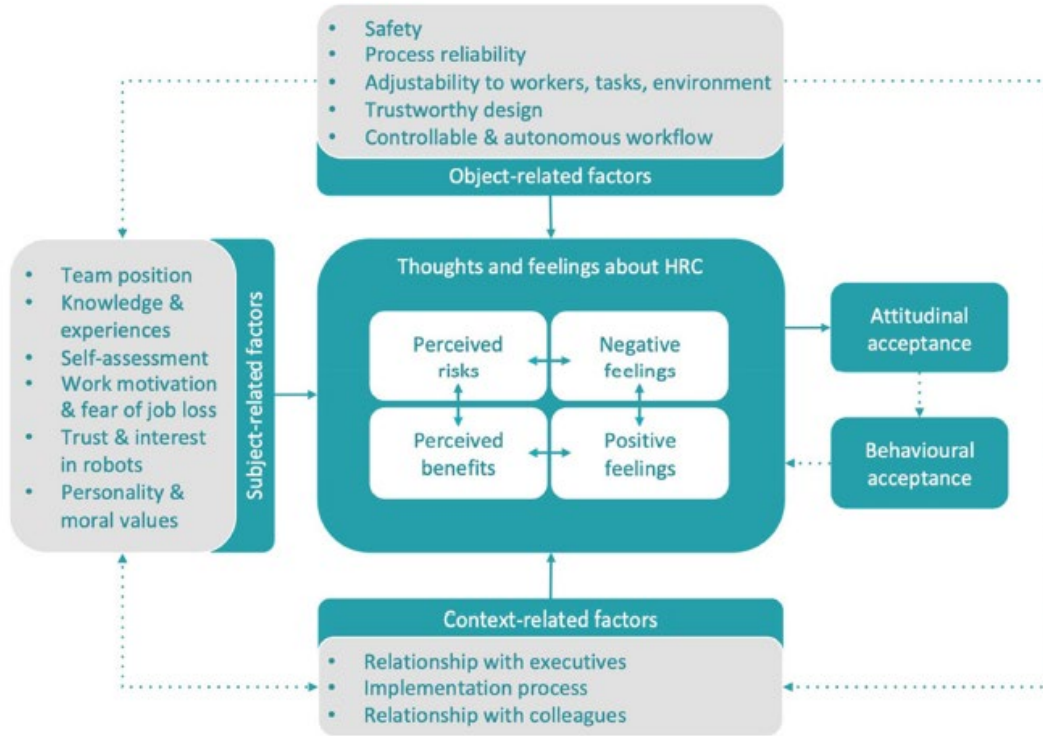


Figure 1: Influencing factors on assembly workers' HRC acceptance chart created by Meissner et al. Dashed arrows refer to optional interactions.

Müller-Abdelrazeq et al. went a step further by conducting an experiment to analyze how attitudes are influenced through interaction [52]. The participants with more robot-related experience showed a more positive attitude towards collaborative robots. Furthermore, since the participants were evaluated before and after the interaction, the authors were able to conclude that even after a short positive interaction with the robot, attitudes improved. This demonstrated that a positive experience with a robot had a positive effect on the attitude towards collaborative robots.

Acceptance becomes an issue as soon as technology is deployed. An example is described by Wurhofer et al., who was able to further investigate how operators'



acceptance changes over time by evaluating expectations before the deployment of robots, while the operators are learning and training with the robots, and after the operators become familiar with the robots as seen in Figure 2 [55]. Not only was the shift in operator opinions observed but also how much the operator was impacted by the implementation of the robot. In the beginning there was uncertainty as well as skepticism and rejection because the operators expected the robot to work independently. However, there were some operators who saw the value of implementing robots and looked forward to the interaction. After learning and training with the robot the complexity of the operator's job increased, the operator had to adapt to the robots and feelings of noninvolvement, resignation or malicious joy were developed by the operator. Noninvolvement stemmed from not being able to contribute to the implementation process of the robot, resignation was the acceptance that the operators had no choice in the matter, and malicious joy was when the operators were happy that something went wrong with the robot. One of the participants commented that if the operators had been involved then they would have told the management about problems beforehand, but management never asked for the operators' opinions. The implementation process taken by the company resulted in unhappy operators. In conclusion, it was determined that it is crucial to involve the operators in the implementation process to foster acceptance and provide guidance on the best way to use the robot in production.

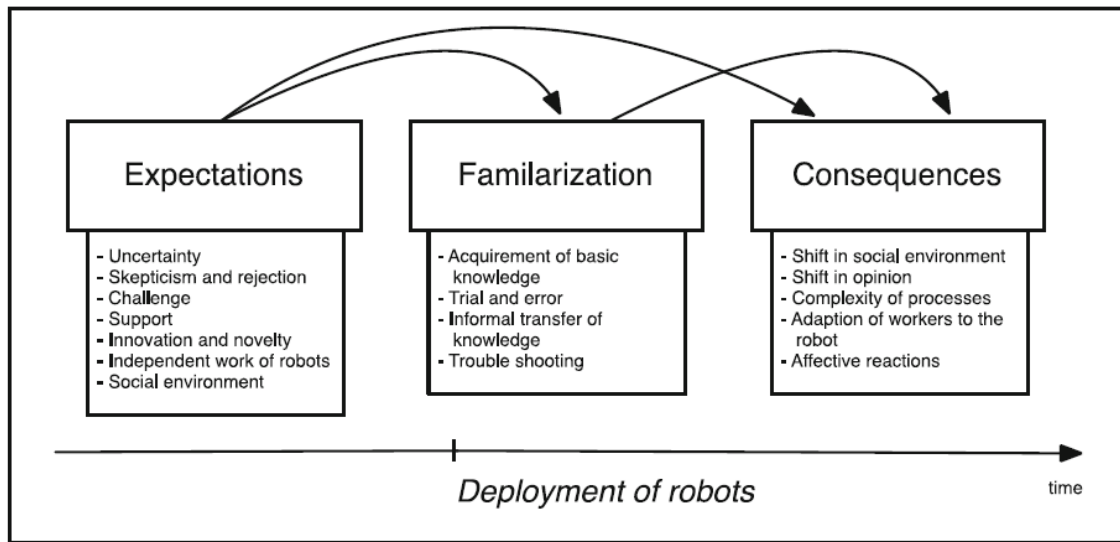


Figure 2: Phases in the deployment of robots and associated experiences of workers created by Wurhofer et al. while investigating user's acceptance over time.

A safe and well-designed robotic system may be necessary, but it is not sufficient for the acceptance of HRC because HRC acceptance is not solely a technological issue. Feelings of uncertainty, loss of control, and anxiety are found to play a negative role in operators' attitudes. In fact, control becomes a very important topic in HRC. As Stadnicka and Antonelli mention, it is important to empower operators with additional control in order to foster acceptance of the system [56]. Overall, operators are mostly concerned about their physical and mental well-being and fulfilling requirements like efficiency and product quality [57]. The operators want to know that the robot will benefit them and will not slow down their work process. The operators must see benefit in working with the robot to accept the robot.

Many operators make assumptions and have expectations about what a robot can do and how they work. When the robot falls short of these expectations it can generate

negativity towards the robots. Meissner et al. concluded that, high expectations lead to quick disappointment [50]. When the operator expects the robot to make mistakes just like another human would, they are less annoyed by malfunctions. In order to ensure that their expectations are realistic the operator must have a clear mental model of what the robot is capable of. Therefore, shared mental models are important for acceptance.

### *Research Gaps*

While a lot of researchers investigate acceptance with surveys and interviews and generate suggestions and solutions for acceptance, not many discuss using the operator's feedback to generate requirements that can be used for designing a workstation. Wurhofer et al.'s work demonstrates a need for a better implementation process that does not leave operators feeling unaccepting of working with robots. It is also evident that their feedback could help prevent future production issues with the robot. Ideally the work done in my thesis will lead to an implantation process that leaves operators feeling accepting of working with robots and leads to improved efficiency and collaboration.

### **Comfort**

Human comfort has a direct and immediate influence on collaboration quality, task efficiency, and human acceptance in a human-robot team [10]. However, the variability in the perception of comfort makes it hard to ensure operators will feel comfortable. This is because it is subjective and can be affected by many factors causing comfort to vary from operator to operator even if they are put in the exact same situation. For example, some operators may feel nervous and uncomfortable about a robot being in close proximity. Another operator may feel impatient since an increased distance from the robot can

increase the time it takes to hand over a tool or part. Wang et al. states, the general factors that have an impact on an operator's feelings towards robots include robot movement trajectory, human-robot proximity, robot speed, position of object delivery, and interaction-time cost [30].

The speed of the robot's response directly influences operator comfort [49]. On one hand a slow robot might make an operator feel safe, while on the other hand a different operator could feel uncomfortable and think the robot is less efficient. Other operators may grow impatient and become frustrated with having to wait on a robot. There has been research conducted by Sisbot et al. that discusses the concept of a human-aware motion planner that infers operator preferences in order to adapt the robot's speed [58].

Robot movement trajectories also play a role in comfort. When a robot reaches for something, the operator may prefer that the robot picks a path that is further away from the operator. Dragon et al. conducted an investigation on how motion planning could be centered around the comfort of the operator instead of completing the task [59]. Robot proximity is defined by how close the robot is to the human. Stark et al. conducted a study that evaluated how comfort changed when the robot reached into the operator's personal space [60]. Walters investigated the idea that the proximity an operator prefers to another operator could be comparable to the proximity that they would prefer to a robot [61]. This study demonstrated that the distance between the operator and the robot is very subjective and depends on whether the operator views the robot as a 'social entity'.

Fluency within the collaboration is another factor that can impact operator comfort and task efficiency [49]. Fluency is more about the quality of the interaction and can be

both objective and subjective [62]. Subjective fluency focuses on perceived fluency and is influenced by the level of trust the human puts in the robot, the perceived contribution of the robot, and if the robot demonstrates good teammate traits. Objective fluency depends on the amount of concurrent tasks completed, how long the operator or the robot is idle, and the robot's delay time [10]. Cakmak et al. conducted a study to create robot-human fluency that comes close to the fluency found in human teams [63]. Other solutions include developing operator intention anticipation for robot action selection, human-inspired plan execution systems, and perceptual symbol practice [49]. These solutions focused on making the robot's intentions clear in order to create a more natural interaction with the operator to make them feel more comfortable and confident about the robot's appropriate response.

The amount of effort that the operator must put into coding the robot also impacts comfort. Teaching pendants, a hand-held device that can be used to program the robot, can make the operator feel uncomfortable due to how tedious and time consuming they can be [49]. In order to come up with a way to make the process more comfortable a teaching-learning collaboration model was proposed by Wang et al., where the robot learns from demonstrations and verbal communication [64]. This proved to efficiently increase operator comfort during collaboration.

### *Preferences and Adaptivity*

A robot that executes predefined working steps impedes the operator in terms of flexibility and speed. This can lead to a decrease in productivity due to the change in working routine for the operator. Wang et al. mentions that accommodating the robot's

actions to different operators by considering their work preferences can improve the comfort of the operator [49]. Wang's proposed solutions to accommodating the robot's actions to different operators is to adjust human-robot proximity, design multiple robot motion trajectories, control the robot with diverse velocities, and plan the robot with different manipulation orientations.

In order for the robot to meet operator preferences it must be adaptable. In fact, adaptability has been found to be a key requirement in human-robot interaction. The interview conducted by Weiss and Huber demonstrated that the lack of flexibility that comes with working with a robot that is not adaptive is at least partly responsible for the other shortcomings in perceived safety, usability, and general helpfulness [65]. One way that robots can adapt to their operator is by taking individual working steps and speed into account. Mitsunaga et al. mention that subconsciously operators adapt their behavior to communicate with other operators in order to make interactions run smoothly. This same principle can be applied to human-robot interactions [66]. In past research, operators were expected to consciously give feedback, but that led to interference with the aim of the interaction. Mitsunaga et al. proposed an adaptation mechanism based on reinforcement learning by reading subconscious body signals from the human partner [66]. One key issue with this method is that operator preferences can be interdependent. For example, the discomfort of personal space invasion is lessened if gaze meeting is avoided. An operator's feeling of a comfortable distance for a robot varies with how menacing the robot's actions are perceived to be, such as how fast it moves. This means that a system that adapts to personal preferences has to consider several parameters simultaneously. Operators also

display their discomfort in different ways, so it may be difficult for the robot to recognize the signs of discomfort across multiple operators. The study conducted by Mitsunaga et al. also found that it can be very difficult to measure true preferences [66]. Sometimes an operator's stated preference may not match up with their preferences during the interaction with the robot.

Kim et al. focuses on adaptivity that can improve ergonomics in an adaptable workstation [67]. Musculoskeletal disorders are the leading work-related injuries in manufacturing. These injuries can only be mitigated by ergonomically efficient workstations. Since all operators are different shapes, sizes, and ages, workstations should ideally be adapted to individual operators in real time to prevent these injuries when possible. Regularly adapting a workstation can be challenging but one solution lies in developing a reconfigurable human-robot collaboration workstation. A workstation where the robot can move to help improve the operator's ergonomics. Detecting the tools and parts in the workspace could improve ergonomics and allow for live adaptation to the operator's pose, overloading torques, manipulating hand positional variations, preferred working location, and task conditions [67].

### *Research Gap*

Majority of the solutions found by researchers focus on providing the operator with comfort by ensuring the robot adapts to their preferences. Approaching comfort in this way makes it possible to deal with the subjectivity of comfort as well as the subjectivity of acceptance. However, it may not be possible to develop a system with the ability to meet every unique need of each operator. Ideally, the work done in this thesis will provide the

tools a company would need to be able to determine what the most important features are for the operators designated to work at the collaborative workstations.

### **Human-Robot Teams**

The results found by Shah et al. suggest that human-robot teamwork is improved when a robot emulates the behaviors and teamwork strategies used in human teams [68]. Typically, robots are treated like tools and given step by step commands and instructions. However, in human only teams this kind of explicit instruction is not an efficient way to coordinate actions of multiple team members. The most effective team members anticipate what their other team members need and adapt to the actions of others [68], [69]. Good team members tend to distribute work among team members on-the-fly, frequently communicate updates on the status of a task, and have shared mental models that allow the team to consider the consequences of their actions on others.

Mental models are used to help operators perceive and interpret the robot's intentions and actions. Unfortunately, operators tend to have an incomplete or even inaccurate mental models of their robot partner. Operators find it hard to create mental models of robots that allow the operator to accurately determine the robot companion's behaviors and performance [48]. The inability to create a shared mental model can lead to the operator overestimating or underestimating the abilities of the robot which is described as misuse and disuse [57]. Misuse and disuse can be detrimental and lead to an unbalanced team and reduced human-robot teamwork efficiency [48]. It is vital for the operator to hold a sufficiently developed mental model of the robot and the robot's capabilities. The solution proposed by Charalambous ensures that during training operators are not only



taught how to use the robot but what the robot is capable of achieving [57]. Knowing what the robot is capable of doing would help raise operators' awareness regarding the ability and limitations of the robot and assist with matching operators' perceptions with reality.

Perception and interpretation of operator behavior can impact fluency which is needed for acceptance. The robot can have difficulties identifying and determining demands based on body language, hand gestures, activities, etc. without the proper equipment. When the robot struggles to recognize human intentions correctly, poorly timed responses and slow and jittery interactions can occur. This lack of fluency can result in unnatural and inefficient teamwork with increased operator workload [48]. Human-robot teams must be able to observe and understand their teammates' actions, predict their teammates next moves, and direct each other to do work. This requires both the human and the robot to have a shared mental model to facilitate communication and coordination[48].

Shah et al. discusses the use of Chaski, a tool that is designed to mirror the human team's ability to adapt on the fly to other teammates, offer frequent updates on the status of tasks, and act to minimize operator idle time [68]. Chaski aims to make human-robot more like human teams with more natural and fluid interactions. Chaski divides tasks between the robot and operator that will maximize their strengths and minimize their weaknesses, introducing a more fluent interaction. A system like Chaski would be more aware of the robot's capabilities and better at deciding which tasks would be best for the robot and the human.

Just like human teams, human-robot teams must have excellent communication, coordination, and collaboration in order to work efficiently together [48]. The

communication issues can come in the form of high time delays in communication or the inability to understand each other. The inability to understand each other can come from unintuitive or improper modes of communication when processing human attention, predicting actions, and understanding intent from each other. It is important to build user-friendly human-robot interactions in order to simplify the use and operation of a robot and allow for efficient communication. Inefficient collaboration arises within team members who have different goals which can result in delays in task completion and poor quality of work. Operators who fail to check for qualifying capabilities or lack training and proficiency cause improper handoffs or transfer of control between operators and robots. Poor coordination is the mismatch of operators' and robots' abilities when coordinating activity, especially when there are gaps in their capabilities or uncomplimentary skills. Poor team composition will result in a lack of trust and will be detrimental to coordination. Workload issues also play a factor due to the inability of a team member to perform certain tasks. The complexity of the workstation and consequences of its failure need to be considered. Task interruptions and ill-defined tasks may cause setbacks that can confuse team members.

When designing for human-robot teams, engineers should understand the context of human-robot relationships and the dependencies that arise when they work together [48]. Engineers should consider human-robot teams as a unit and consider the roles each member will play. The operator's and robot's abilities and the overall team capabilities should complement each other. The structure of the team affects when, where, and how robots do their work. There are five roles that humans can take when interacting with robots:

supervisor, operator, teammate, mechanic, and bystander. These roles can change as circumstances change which will reshape the team structure. There are four different ways teamwork can be structured: *Play*, *Function Allocation*, *Bid*, and *Interdependency*. *Play* is where the plans are thought out ahead of time and simply need to be carried out with some room for mild adaptation. If the interaction is too constrained it will not be able to handle variances in scenarios. *Function Allocation* is where, early in the design phase, the engineer asks question about who can do what tasks and describes how to make that decision. Then the best fit for the robot and the operator is determined beforehand or during real-life execution. Conducting *Function Allocation* early in the process allows the engineer to fully explore potential combinations of teamwork. The third option is *Bid* where the robot and the operator are responsible for task allocation and select preferences based on their availability, skill set, and time to complete the task. Then the engineer makes the final decision about task allocation based on the preferences. Lastly there is *Interdependency* which implies work is assigned effectively for joint activities through interdependent requirements [48].

Overall it is important to understand the role of operators and robots in the decision-making process [51]. In order to bridge the gap between the perceived value of human and robotic teammates, Gombolay et al. suggests to enhance the robot's autonomy and authority in team decision-making [69]. Robot teammates with the ability to autonomously allocate and schedule tasks can improve both task completion and operator acceptance [69]. Operators may not effectively understand how to utilize robotic teammates with specialized capabilities. Therefore, allowing robots more autonomy over their behavior may help to

counteract these biases and guide operators toward a better understanding of how to best utilize these robots. In this method, the planning fallacy can be avoided. Planning fallacy is when operators underestimate the amount of time, they need to complete a set of tasks or overestimate the amount of time that the robot needs to complete the same set of tasks. Planning fallacy leads to an unbalanced team leaving the operator frustrated at the lack of robot assistance or wondering why they don't have much of a role in the HRC workstation.

### *Research Gap*

Researchers have found a lot of different solutions for promoting efficient human-robot teamwork. There have also been design guidelines created specifically for how a robot should be designed and how a workstation should be designed to promote safety, ergonomics, and efficiency. While these are important, one thing that professionals in industry have said is that a lot of design decisions depend on the process the workstation is being developed for. The goal of this thesis is to not only develop another solution with the use of design requirements but also contribute a process that can be followed to fit any case scenario. A process that will ensure the involvement of the operator and tend to their need for comfort and acceptance in the system.

### **Key Challenges**

Despite the growth of collaborative robots being used in industry, factors influencing workers' acceptance of HRC have not been sufficiently explored [50]. Though HRC has been studied for over sixty years there still is not enough research geared towards the human factors that needs to be considered to allow for a successful implementation of HRC in manufacturing [57]. Even less attention has been paid to the attitudes and needs of

the operators who will be working with these robots [70]. The goal of this thesis is to add to the research field by taking a closer examination at the true customers for collaborative robots, the operators.

Furthermore, while previous research observed various degrees of reactions to different workspace setups, there is limited research to date on the comfort level a human has when the individual can control the way the robot interacts. The first step to address this research question is to determine which of the factors that impact comfort can be used for controllable preferences.

Lotz et al. mentions that it is imperative to address and resolve the operators' concerns in order to achieve efficient collaboration between operators and robots [34]. This thesis attempts to address the operators' concerns by determining the design requirements for a human-robot collaborative assembly station through operator feedback. In this way the author is able to address the operators' feelings of uncertainty, loss of control, and anxiety that is produced when working with robots.

## CHAPTER THREE

### CUSTOMER FEEDBACK

In this chapter the results from the survey and interviews that were conducted to gain manufacturing relevant data are discussed. The survey and interview questions can be found in the Appendix. The survey was deployed to a manufacturing facility. While developing the survey it was important to remember that since it is mandatory for operators to work with robots the attitudes towards using the robot have to be directly investigated in order to reflect operators' actual satisfaction level [50]. After responses from the survey were received, questions for the structured interview were developed. The questions were aimed to further explain the survey responses and to validate the conclusions from the survey.

#### **Purpose of the Study and Research Questions**

The purpose of the survey was to explore how engineers make operators' experience interacting with robots better. Instead of making assumptions, the aim was to ask the operators directly. Asking the operators directly provided an opportunity to identify any diversity in responses that could determine if a personalized approach to the design of a HRC workstation is beneficial for comfort and acceptance. A primary goal was to determine what preferences would be the most important for the operator to be able to control while working with the robot. Specific research questions include: How can the interaction between operators and robots be improved? Is there enough variability in

operator preferences to justify having user-controlled preferences? Which variables do the operators desire to have control over?

## **Method**

### *Design*

To investigate these research questions, a qualitative research approach was used. The data was collected by combining the use of surveys and structured interviews. Ideally the survey would pull results from a larger sample size while the structured interview would allow for a deeper investigation with a smaller sample size. Both methods contained questions used to collect the participants' opinions and perceptions about working with robots.

### *Goal*

Volunteers for the survey and interview were limited. The plan was to deploy a survey first and gather interview participants from the survey. The survey was sent to the Human Resource (HR) department of a company who had access to seven hundred operators between two locations. The two locations have an NAISC code of 541330, Engineering Services, and 423830, Industrial Machinery and Equipment Merchant Wholesaler. The goal was to get a response from at least one hundred operators and then conduct an interview with twenty of the responders. Unfortunately, not many operators responded. This led to a discussion with the HR departments. The location with an NAISC code of 541330 decided to have a production supervisor take the QR code for the survey out on the floor. Having the supervisor take the survey to the workers directly led to more responders. Still there were only twenty-one survey responders and of the twenty-one

responders only four volunteered for a follow-up interview. Of the five responders that volunteered only two responded. This led to the decision to find three other people to interview who could potentially have varying levels of experience and perceptions of working with robots. The lack of responders could be because HR sent the survey to the operator's email. Since operators are always working on the manufacturing floor, they may not have time to fill out a survey during work. Furthermore, during an operator's break they would prefer to relax. Most of the participants that did respond probably came from being allowed to take a break from work to fill out the survey.

### *Participants*

Participants were selected based on having knowledge of the processes of an assembly line. There was a total of twenty-one responses with an age range of eighteen to sixty-four. Approximately 54% of the participants have worked with robots before, but only two of them in a truly collaborative setting. There is also a variety of experience captured within the results including operators who work in assembly, machining, testing, etc. A majority of the responders have worked for the company for more than two years.



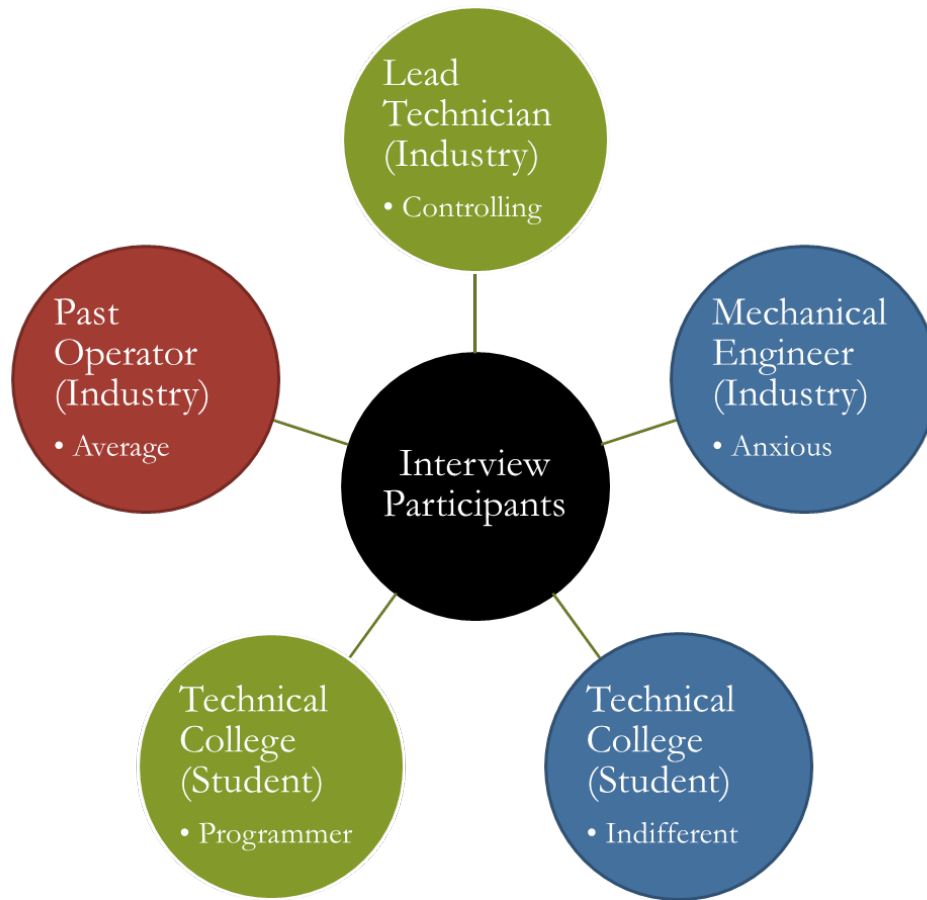


Figure 3: Interview participant categorization. Red represents someone who worked with a machine that contained a robot, blue represents no robot experience and green represents having robot training

Unfortunately, only two of the participants from the survey volunteered and responded to a request for follow-up interviews. However, this led to a more diverse set of responses when it comes to the professional experience of the participants, this diversity can be seen in Figure 3. The participants from the interviews contain a group of five individuals who were selected based on convenience due to the lack of survey responders. Two of the participants are current students from a technical college. Another one of the participants currently works in the industry and majored in Mechanical Engineering. Lastly, two of the participants are current employees of the company the survey was sent

to. One is a lead technician who went through the mechatronics apprenticeship program the company provides. The other is an industrial engineering technician who started off as an operator after going through a CNC machining apprenticeship. Three of the five volunteers have had experience with robots, while two of them did not. None of them truly have experience working with a robot in a collaborative workstation. The age range of all participants is between twenty-four and thirty-four years old. Even though none of these individuals are currently operators, it was still possible to capture five different perspectives regarding working with a robot. In Figure 3 controlling, anxious, average, programmer, and indifferent stand for the perspective the participants had. A controlling perspective stands for someone who needs a great deal of control in a collaborative setting. An anxious perspective stands for someone with a lot of anxiety about working with robots. An indifferent perspective stands for someone who does not have any anxieties but is more concerned with finding a suitable role in this collaborative setting. A programmer perspective stands for someone who is used to programming the robot and knows the importance of using them correctly. An average perspective stands for someone who responded with more neutral views on their feelings towards robots. They were not super anxious about robots, but they were also not indifferent about them. The participants perspectives and past experience heavily influenced their responses. Nevertheless, each participant was asked to speak from the perspective of an operator.

### *Data Collection*

The initial survey was composed of three sections with a total of fifty questions. There were a variety of formats for the questions including multiple choice, text entry,

matrix tables with Likert scales, and ranking. A survey generating software called Qualtrics was used to generate the online survey that participants filled out using email links or QR codes. The first section gathered background information about the participants including their age, experience with technology, years in the company, and past experience with robots. The second section was used to determine the participant's perception and opinions of robots when working with them in an industry setting. Participants responded to questions such as "Is the robot a threat or an opportunity?" and "Do you believe that a robot is there to support you?". It also included questions about positive and negative feelings that the operator may have when considering working with a robot. The third section is composed of questions to investigate suggestions for improving the experience of working with a robot and to determine what preferences the participants have for the interaction with robots. The third section includes questions such as "What can create a team-like experience?", "What would you like to have built into the robot?", and "What would make working with the robot more enjoyable?". The questions that ask about preferences relate to workstyle, communication preferences, and ways to control the robot. All three sections were developed in order to assess the participants' current perception of robots and what can be done to make them more comfortable and accepting of working with robots.

After analyzing the results from the survey, questions were developed for a structured interview. The structured interview was composed of twenty-three questions to help guide the conversation. During some interviews additional questions were asked to help clarify the participant's responses. The structured questions began with asking about the participant's age, current position, professional background, and years working in their

current position. Then the participant was asked about their experience with robots and the opinions and perceptions the participant has about robots. This was followed by questions about anxiety and concerns when working with robots and what could make the participant feel more comfortable, accepting, and excited while working with robots. The next few questions followed a pattern of asking the participant about their preferences and requirements for working with and controlling the robot and then providing them with a list of options to rank. This was done to understand what ideas come to mind before presenting them with the ideas derived from the survey results. Additionally, it helped to determine the importance ranking of the requirements. Then they were asked to compare the idea of adaptable preferences, the current state-of-the-art, to the idea of controlled preferences. It was explained that the controlled preferences would be through an interactive profile that would allow them to input their preferences while learning about the robot's capabilities, the idea the author has for the future of collaborative robots. The interview is concluded with a question about how the participant would prefer to work with a robot in a human-robot kitting workstation. The format of this structured interview allows the author to validate the conclusions made from the survey and investigate the reasoning behind some of the responses. Furthermore, it provides the opportunity to determine if the correct task allocation approach was used in the case study that will be discussed in Chapter five and how the adaptive approach compares to the user-controlled preference approach.

### *Data Analysis*

In order to analyze the data from the survey the results were put into Excel and divided into four categories: opinions, communication style preferences, work style

preferences, and user-controlled preferences. The results placed in the opinion sections were categorized as positive, negative, and neutral opinions or feelings towards robots. If the questions had responses that fell along a five-point Likert scale, then the responses were redistributed. For example, *somewhat agree* and *agree* were placed into the positive category, *neither disagree or agree* were placed into the neutral category, and *somewhat disagree* and *disagree* were placed into the negative category. The results placed into the communication style section were further divided up into eight categories: delayed, immediate, demonstration, verbal, body language, tactile, visual, and audial. Delayed and immediate relate to how quickly the participant would like to receive feedback while working. Demonstration, verbal, and body language relate to how participants would like to communicate to the robot. Verbal refers to speaking and giving instructions to the robot. Body language refers to using gestures or facial expressions. Demonstration refers to showing the robot what the user wants it to do. Tactile, visual, and audial relates to how the participant would like to receive feedback from the robot. Tactile refers to feeling vibration from a wearable device. Visual refers to using lights or monitors. Audial refers to the robot speaking to the participant. Within these categories the responses are again categorized into yes, no, and neutral in the same way the previous section categorized positive, negative, and neutral. The results placed into the user-controlled preferences section is composed of the results from ranking the aspects the participants would like to control as well as the desired control level. The desired control level is ranked by minimal, moderate, and maximum with *none at all* and *a little* falling into the minimal category, *a moderate amount* falling into the moderate category and *a lot* and *a great deal* falling into

the maximum category. This method was used to develop a visual representation of the results in order to conduct a descriptive analysis.

In order to analyze the interview results they were first transcribed using Microsoft Word's dictate functionality. Then the thematic analysis method described by Maguire et al. was used [71]. Since the author is concerned with addressing specific research questions, the theoretical thematic analysis method was used. The steps in this process are as follows: become familiar with the data, generate initial codes, search for themes, review themes, define themes, and write-up. The open coding method was used which means that the codes were determined as the author was reading through the transcripts. Instead of coding each individual line, the codes were only used for phrases that related to the thesis or captured something interesting. Then the codes were typed into themes which were reviewed and redefined. The final themes produced were: general opinion on collaborative robots, reasons for anxiety and concerns while working with robots, fear of job loss during implementation, feeling more comfortable and accepting of robots, communication and work style preferences, the importance of control, requirements and features for HRC, and adaptive preferences vs controllable preferences. Figure 4 shows a map of the major themes and their subthemes. The theme of feeling more comfortable and accepting of robots is an overarching theme that is rooted in all the other themes. The requirements for interacting with robots, the importance of control in a collaborative setting, interaction preferences, and opinions on collaborative robots can be used to improve operator comfort and acceptance towards robots.

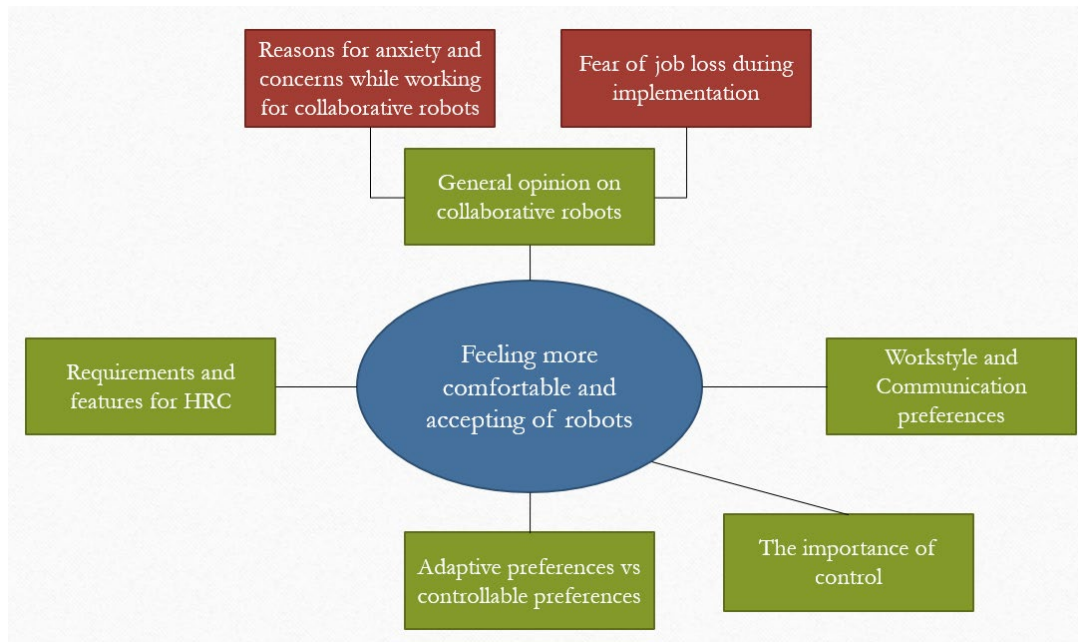


Figure 4: Thematic Map

## Survey Results

### *The Opinions of the Participants*

In order to gauge the feelings that the survey participants have towards robots, a series of questions were asked, which can be found in Table 2. The questions with an asterisk (\*) by it, represent questions that had to be reverse coded.

Table 2: Questions used to determine participant's feelings towards robots.

Questions	Positive	Neutral	Negative
*I view working with a robot as a threat.	20	-	1
I view working with a robot as an opportunity.	19	-	2
I believe that robots are reliable.	15	-	6
I feel safe while working with a robot.	16	-	5
I enjoy working with a robot.	11	6	4
Working with a robot _ my efficiency.	15	2	4
I feel like a valuable employee while working with a robot.	10	4	7
While working with a robot I feel challenged in a good way.	7	6	8
While working with a robot I feel happy.	9	3	9
While working with a robot I feel excitement.	6	2	13
While working with a robot I feel productive.	10	2	9
*While working with a robot I feel helpless.	19	1	1
*While working with a robot I feel impatient.	17	2	2
*While working with a robot I feel frustrated.	14	3	4
*While working with a robot I feel anxious.	18	1	2
Do you believe that a robot is there to support you?	16	-	5
Do you believe that robot is there to assist you?	18	-	3
Total	240	32	85

The responses from these questions were divided into three categories: positive, negative, and neutral. In Figure 5, a pie chart is used to highlight the response categories. Overall, sixty seven percent of the responses were positive. Because there was a high positive percentage, it can be concluded that the robot itself may not be the only problem but rather the way the robots are implemented. This conclusion led to the inclusion of questions in the interviews about what causes concerns and anxiety while working with the robot.



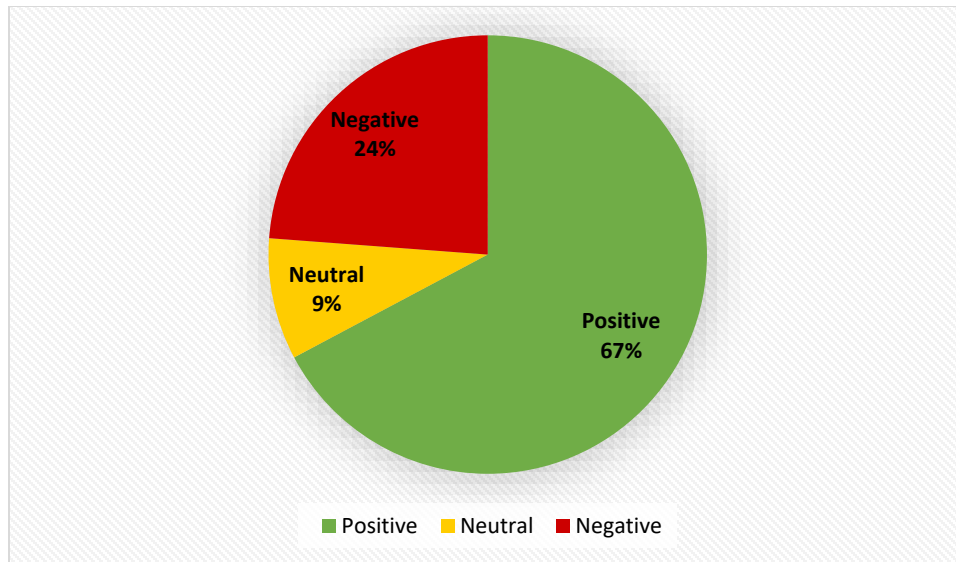


Figure 5: Feelings Towards Robots

For each individual question in the survey majority of the responses were positive as seen in Figure 5, especially questions about viewing a robot as an opportunity and not a threat, as well as believing that the robots are reliable and have the ability to improve efficiency. However, questions that asked about feeling challenged, happy, excited, valuable, and productive did not yield as many positive responses. For feelings of excitement and being challenged the negative responses outweighed the positive responses. For feelings of being happy and productive the responses were nearly tied. When it comes to the responses for feeling like a valuable employee the positive responses only outweighed the negative response ten to seven. The results from these five questions are the most concerning and should be considered when considering how to improve operator experiences with robots.

### Communication Style Preferences

The questions and results for communication style preferences can be seen in Table 3 and Figure 6.

Table 3: Questions used to determine preferred communication styles.

Questions	Yes	Neutral	No
I prefer to receive feedback I can hear (my robot speaking to me)	14	4	3
I prefer to receive feedback I can see (using a monitor or lights)	17	3	1
I prefer to receive feedback I can feel (vibration from a device)	12	6	3
I prefer to communicate using body language (gestures, facial expressions)	6	10	5
I prefer to communicate by talking (giving instructions)	15	3	3
I prefer to communicate by demonstration (showing my robot what I want it to do)	14	5	2
I prefer to receive immediate feedback even if it interrupts what I am doing	10	8	3
I would prefer to receive feedback after completing a task	16	5	0

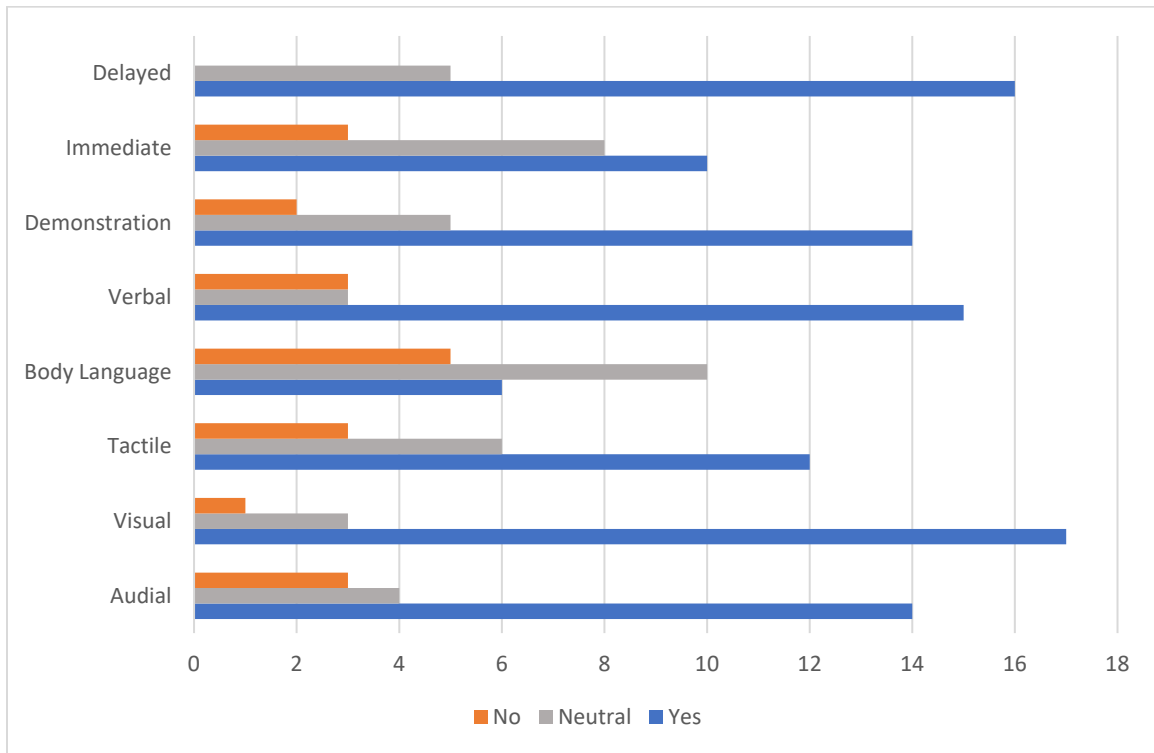


Figure 6: Communication style preferences

It can be observed from Figure 6 that each communication style has some variety in responses. There are three categories of responses: timing, receiving feedback, and

providing information. Delayed feedback seems to be more popular than immediate feedback. Giving instructions and showing the robot what to do seem to equally outweigh body language as an option for providing information. Lastly, using a monitor and lights to receive feedback seem to overshadow the option for the robot to speak or a wearable device to vibrate. Unfortunately, these results do not do a good job of sufficiently highlighting which preferences would be preferred over others. This should be considered in future work.

### *Work Style Preferences*

The questions and results for work style preferences can be seen in Table 4 and Figure 7.

Table 4: Work style preferences table

Work Style	Yes	Neutral	No
I would prefer my robot (team member) to follow my lead	18	3	0
I would prefer my robot (team member) to give me suggestions	10	5	6
I would prefer to work in close proximity with my robot	9	10	2
I would prefer my robot to be further away from me	7	12	2
When working in a team, I would prefer to split up tasks and work separately	9	9	3
When working in a team, I would prefer to work on tasks together	11	9	1
Would you prefer your robot to work at your own pace	18	0	3

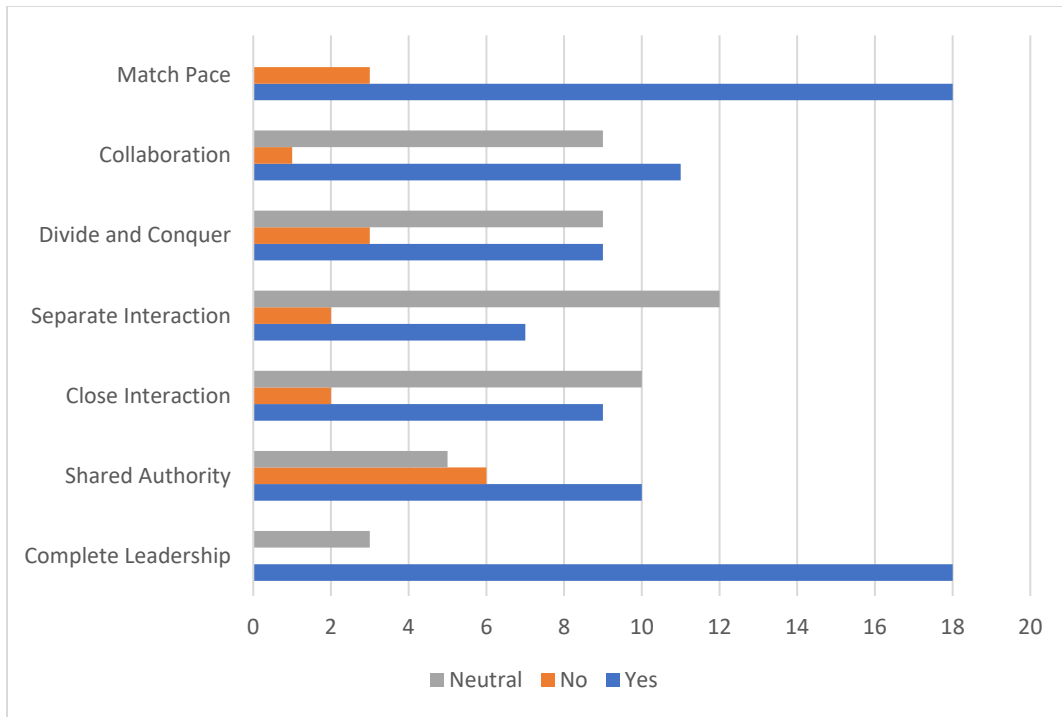


Figure 7: Work style preferences

Based on the results in Figure 7 more operators prefer complete leadership over shared authority. There is a more neutral opinion about the proximity to the robot and a tied response between divide and conquer and working on tasks together. One thing that is evident in the results is that majority of the participants would prefer for the robot to match their pace.

### *Preferences for Control*

The preferences for control were captured in the pie chart in Figure 8 and the graph in Figure 9.

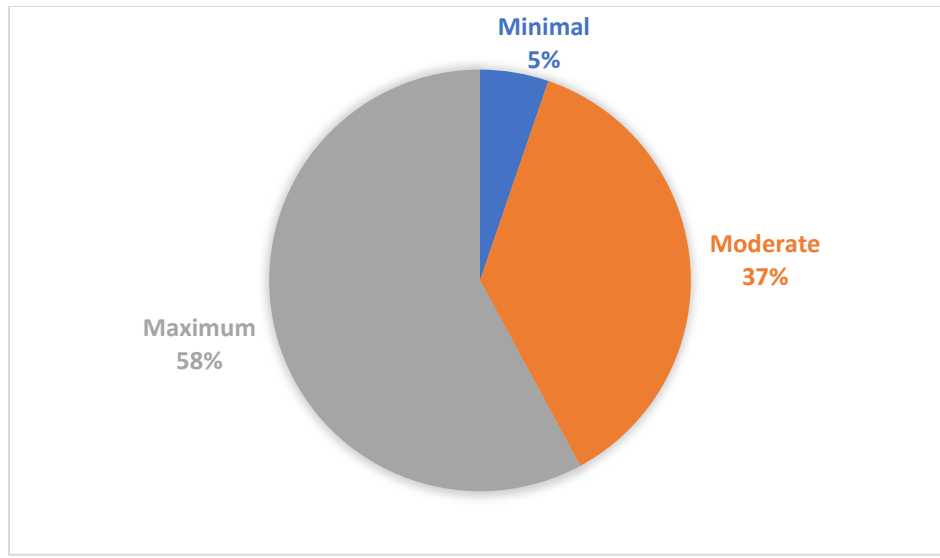


Figure 8: Desired level of control.

In Figure 8 the desired level of control chart shows that there was variety in the participants' desire to have control over the robot. Fifty eight percent of the participants prefer to have a lot of control over the robot, but there were still some who only prefer moderate control. Because there was a variety, it can be concluded that there are a variety of reasons behind the need for control which led to the inclusion of questions about the importance of control in the interview.

In Table 5 the options that were ranked for the user-controlled preferences can be found. Each participant had the opportunity to rank each option in order from one to five. It is easier to see how the distribution falls in Figure 9.

Table 5: Importance ranking for user-controlled preferences

User-Controlled Preferences	First	Second	Third	Fourth	Fifth
Controlling how fast or slow your robot moves	8	3	5	2	0
Controlling how you and your robot communicate with each other	5	7	4	1	2
Controlling how you and your robot interact (working on task's together or separately)	5	5	5	2	2
Controlling how close your robot is to you when it is not moving	0	2	2	9	6
Controlling how close your robot is to you when it is moving	0	2	3	5	9

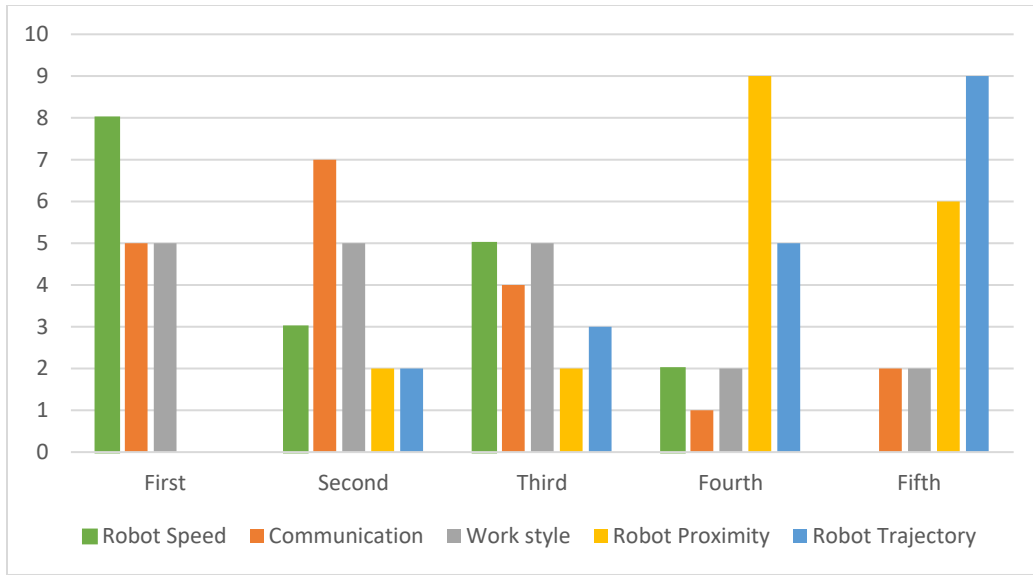


Figure 9: User-controlled preference priority

Based on Figure 9, robot speed, communication, and work style were most ranked as the top three preferences to control. Robot trajectory and robot proximity were most ranked fourth and fifth but still showed up in the second and third place. Robot trajectory and robot proximity seem to not be as important as the other preferences to the participants in this survey.

## **General Findings from Survey**

The positive feelings towards robots outweighing the negative feelings implies that operators may not have a problem with the robots themselves but rather the way they are implemented. This is supported by Meissner et al.'s findings which determined that though many workers approved of collaborative robots, they have a negative attitude towards the introduction of HRC due to reasons not related to the technology itself [50].

When it comes to the controllable preferences robot speed is the most important, followed by communication style and work style. Participants fall into the yes category for multiple communication and working preference with many of the other participants falling into the neutral category. The amount of neutral responses could indicate that participants may not know for sure which style they prefer over others. Alternatively, the amount of neutral responses could suggest a flaw in the format of the survey since the format does not force the participant to choose between decisions such as visual versus audio feedback.

## **Interview Results**

### *General opinion on collaborative robots*

Unsurprisingly, it was further confirmed in the interviews that not all the anxiety of working with robots is centered around the robot itself. In fact, all five of the participants agree that cobots are beneficial. Even the participant who felt indifferent about the cobots stated that cobots are the future of manufacturing. The participants described the cobots as better with consistency, accuracy, and workload. Furthermore, cobots add more quality and efficiency to the manufacturing process and are even cost effective. However, it was agreed that the benefits from cobots can only be gained if cobots are understood and implemented

correctly and with the proper safety measures in place. One participant even stated that the cobots implementation should be dependent on the process the company wants to complete. If the process is better off being done by a single operator or a single robot than a cobot is not needed. A company should ensure that the process they want to use the cobot for truly needs the advantages of combining operators and robots.

The concerns for implementation also relate to job loss. Although none of the participants are personally impacted by the possibility of job loss due to the implementation of a robot, the participants do feel it would be a concern if they were operators. It was stated that robots can and sometimes do remove jobs, especially since human error is considered to be one of the key inefficiencies in manufacturing. Robots can reduce the number of non-skilled workers, which is why one of the participant's goals is to choose a career that would still allow them to have a job in this advancing industry. One of the participants stated that jobs such as technicians, electricians, and the individuals that collaborate directly with the robot will survive while the nontechnical jobs will fade out. One of the participants mentioned that ideally this would allow workers the opportunity to move up instead of being fired. Implementing the collaborative robots for the sole purpose of assisting an operator does leave some participants feeling less anxious and more comfortable and accepting of the robots, but other participants are not convinced. For example, a human-robot team could double production and with that improvement could come the need for less operators. Another participant mentioned the possibility of the company also deciding to have two robots work together in order to remove possible human error. It is clear from



these statements about being replaced by the robot, that the participants feel there is a lack of protection for the jobs of the operators.

Outside of the job concerns there are other reasons that cause the participants to feel anxious and concerned about the idea of working with robots. The main concern is safety. Afterall, as one of the participants pointed out, the robot does not have an ethical mindset. The robot does not know that it could hurt someone unless it is programmed to be safe. The participants want to be guaranteed that they will not be harmed while working with the robot. Furthermore, before working with the robot some of them would prefer that the robot undergoes extensive testing in different scenarios to ensure that the robot will function properly and not cause any danger. This extensive testing would ensure the robot would be prepared for any unfamiliar situations. While the technology is still new, it will be hard for some of the participants to not feel anxious. There are also concerns about the ability to maintain these robots. If something does go wrong, some of the participants would feel more comfortable if they were able to fix the issue. This is related to another topic that impacts the participants' anxiety, a lack of experience and training with the robots. Before working in full production with the collaborative robots these participants would like to have a chance to learn more about the robots and test out the robot's capabilities. Being able to have time to become familiar with the robot and the process would allow the participant to become more comfortable and accepting of working with the robot. The participants want to be able to develop a better understanding of how the robot works. Some participants even want to go further and learn about the programming of the robot as well.

### *Work Style and Communication Preferences*

Based on feedback from the participants, the participants would feel happiness, excitement, and valuable working with a robot collaboratively. The participants want to be able to work side by side with the robot and do a variety of tasks. What the participants do not want is to do a repetitive task or be forced to watch the robot work. One participant stated that being able to help fulfill a purpose while working collaboratively with the robot would be the best way to enjoy the interaction. When asked what the participants' working preferences were most of the participants stated that it depended on the situation. While for most participants simultaneous collaboration was preferred, the participants realized that some scenarios may call for the need to divide and conquer. The participant that felt indifferent about working with robots preferred more of a supervisor role to the robot. The indifferent participant would be there for the robot to ensure that it was working properly and had everything it needed. In contrast another participant stated that it would be better if the robot assists instead of having its own job. Afterall, working together would be more effective and would allow the two operator and the robot to combine their strengths. When discussing other work style preferences, it was found that most participants felt indifferent about the distance between themselves and the robot as long as safety procedures were put in place. What was really important to the participants was that the robot matched their pace.

To gauge the participants working preferences in a real example each participant was asked the following question: "Imagine this: Your boss tells you that you will be placed at a new workstation with a collaborative robot. There will be no fence around the robot,

but the proper safety measures will be put in place. The product that this workstation would be producing are kitting orders. These kits would contain material such as screws, bolts, nuts, and gussets that can be used with aluminum extrusion to build things. Each kit contains up to six different components and each order can contain up to three hundred identical kits. There are thirty-eight unique components and twenty-six unique kits. Components must be picked and then placed into a bag that needs to be labeled and placed into a box for shipping. How would you prefer to work with the robot in this setting?” One of the participants felt like they would not really have a job in this workstation setting and decided to divide up the tasks of picking the parts with the robot. A different participant felt like sharing the task of picking parts would lead to confusion and that the robot should have the sole responsibility of picking the parts while the participant would supply the robot and make sure the robot is doing its job correctly. The other three participants provided similar answers of allowing the robot to do all of the picking and placing while they supply the robot.

When it came to the communication preferences there was a common desire for a visual communication method. Many of the participants stated that in a manufacturing setting it can be hard to hear or give verbal commands that can be understood. Therefore, it is better to use HMI screens, graphics, and light indications for communication. A teaching pendant was also preferred by the participant with experience with programming robots. One participant also preferred to give instructions through a teaching mode in order to show the robot what they wanted it to do through demonstration.

### *The Importance of Control*

Except for the participant that felt indifferent to robots, having more control would allow for the participants to feel more comfort and acceptance toward the robots. Even though the interview participants were a small sample size, there was a spectrum of desired control among the participants. The controlling participant felt that more control equaled less risk of getting hurt. However, on the opposite end of the spectrum the anxious participant felt that more control was unsafe. The anxious participant preferred to have limited control in order to reduce mistakes or accidents.

There were also variations in the kind of control that the participants wanted. When prompted without suggestions, participants listed the following as desired features to control: the way it assists, the speed, height for positioning, part placement location, robot trajectory, and working style. The importance of controlling some of these features was also discussed. For example, while controlling the speed can prevent the robot from overproducing or the operator from waiting on the robot it can also become a safety issue. A couple of the participants mentioned how the inability to keep up with the robot could be dangerous. The operator could hurt themselves trying to move quicker than they are capable of or the operator could feel so rushed that they make a mistake. One participant mentioned, it is much better to be able to control the speed and start off slowly and then increase the speed as the operator feels more comfortable. The ability to control the robot trajectory not only allows the operator to feel comfortable with the robot staying out of the operator's personal space, but as one participant mentioned it helps to ensure the robot will not collide with the operator by accident. Through these discussions it was clear that

controlling preferences is not only about comfort but safety as well. However, it was stated by a few participants that control should be given to the operator with caution; it should not be given at the expense of efficiency.

### *Adaptable Preferences vs Controllable Preferences*

When asked the following questions about adaptable preferences and controllable preferences an interesting discussion was sparked. The participants were asked how they felt about a robot that adapts to their preferences over time, to which they all responded with approval and interest. They felt like an adaptive robot would be able to match their pace, learn and figure out where improvements could be made, and allow them to spend less time teaching the robot. When compared to the controllable preferences the participants felt that it was better that the robot learn to adapt on its own. One participant stated that this would allow the engineer and programmer to have control over how the robot adapts, making the overall process more efficient. Furthermore, even though one participant was worried about the adaptive robot making the wrong assumptions another participant pointed out that it would be able to use several factors to avoid assumptions since it gathers a lot of data over time.

Controlled preferences were introduced as an interactive profile that allows the operator to let the robot know their preferences and provide the operator with information about the robot's capabilities. The concept of controlled preferences was met with approval and interest. However, the concept was also met with more criticism. Although controlled preferences would make work more personal and enjoyable for the operator, it would be bad for engineers and managers. While operators are trying to make it easier for

themselves, the operator could reduce efficiency and increase takt time since they have not done the research to truly know what is best. One participant stated that each operator could have a different method when only one is truly correct. While it could be beneficial if someone finds a better way to do something, user-controlled preferences would introduce deviations into production and cycle time. The deviations in production can make it difficult to determine why something went wrong since each operator is doing it a different way.

The controlling participant preferred the controlled preferences over the adaptable preferences. This was due to the fact that the change would be immediate. The operator would not have to wait for the robot to adapt to them, and the at the start of a shift the operator could go in and set what is best for their current needs. Some of the participants stated that they would enjoy being able to learn about the robot's capabilities through the interactive profile. It allows for the operator to have a better understanding of what is going on. Overall, the participants felt like both options would be very important, but a majority felt like the adaptive robot was the best for now. The participants stated that if controlled preferences were used, the controlled preferences would need to be limited so that the robot is not too easy to control and manipulate. The preferences would also need to be applicable to the job.

#### *Overall Requirements and Features for HRC*

When the participants were asked what requirements, they would have for working with a robot and what features would meet these requirements there were a variety of answers. However, there was one answer that all the participants had in common, and that

was safety. Some participants specifically mentioned the need for force resistance sensors on the robot to ensure that the robot stops on contact. There were also mentions of a safety zone or invisible safety barrier that the operator would be able to cross to interact with the robot physically but that the robot would not be able to enter. Additionally, there must be E-stops on the workstation and easily accessible controls in order to ensure quick delivery of emergency stops and commands. Other requirements include the need for the robot to be value adding. According to all of the participants, if the robot does not serve a purpose then nothing else matters. Another requirement would be for the company to conduct research to ensure that the application of the robot will be useful.

The average participant also mentioned structural requirements such as a strong foundation for the robot. The average participant suggested adaptable and modular end effectors as well, so that the robot would have the ability to function for a process that requires a lot of variability. A cycle counter would also be helpful to have inside of the robot so that it can keep track of how many cycles it completes. This would be useful for tracking productivity. More requirements for the robot include labels for wiring, standardized parts that are easy to replace, and water resistance in case the sprinkling system inside of a factory goes off.

The anxious participant was focused more on the operator and suggested a training system so that the operator would be able to know everything about the functionality of the workstation and potential dangers that come with working with the robot. Furthermore, the importance of a user-friendly interface with graphics that are intuitive was also emphasized by the anxious participant. The anxious participant felt that the design of the HMI would

be very important. This feature could help with allowing the operator to know what is going on, see that the robot has received commands, and know that the commands are being followed. This was the same participant who did not agree that operators need access to the teachable feature but believes it should be a requirement so that the company has the ability to reprogram it and use it for another application

Lastly some participants desired for the workstation to include a teach pendant, for the operator to have complete control and a need for a detailed process plan. No one was focused on extra features such as heart monitoring. One participant mentioned the inclusion of extra features seemed gimmicky and would be seen as an extra thing that the operator would have to do even though it does not pertain to the job.

### General Findings from Interviews

It was clear as the author was conducting the interview that the previous and current experience of the participants heavily influenced their responses. This demonstrated the subjectivity of the topic of preferences and comfort. Furthermore, when participants were asked to rank the features they would like to control, none of the participants had completely identical responses as can be seen from Table 6. There is clearly a need for a personalized experience; however, based on the discussion any personalized experience would have to be very limited.

Table 6: Priority of controllable features from interview participants.

Response 1	Response 2	Response 3	Response 4	Response 5
Trajectory	Working Style	Working Style	Trajectory	Communication
Placement	Trajectory	Communication	Communication	Speed
Communication	Communication	Placement	Speed	Trajectory
Working Style	Speed	Trajectory	Working Style	Placement
Speed	Placement	Speed	Placement	Working Style



The results also show that the general anxiety that comes from the idea of working with robots may take several years to dissipate. Just like any new technology, operators need time to get used to the idea of working with robots. However, it seems when an operator has experience working with robots, over time that anxiety reduces. The robots themselves are also not the only thing that give humans anxiety. Based on the results the way they are implemented also plays a role as well as the operator's lack of knowledge about their capabilities. Furthermore, the fact that companies have the ability to replace humans with robots, even if they are collaborative robots designed to work with humans, will always be in the back of an operator's mind.

## **Summary**

The goals of the survey were to answer the following questions: How can the interaction between humans and robots be improved? Is there enough diversity in user preferences to justify having user-controlled preferences? Which variables do the users desire to have control over? From the survey and the interview it can be determined a combination of fulfilling requirements, providing the operator with more understanding of robot capabilities, exposure to working with robots, and providing the user with limited control could lead to an improved interaction between humans and robots. The fact that the interview responses had so much variability even though it only involved five people also alludes to the idea that there is enough diversity to justify user-controlled preferences. However, a crucial need to balance the personalization of the experience for the operator with the needs of production has been identified. This will also impact what variables the

users will be allowed to have control over. The following chapters will further explore these topics.

## CHAPTER FOUR

### QUALITY FUNCTION DEPLOYMENT

The objective of this chapter is to use the Quality Function Deployment (QFD) tool to translate the vague operator requirements captured in the surveys and interviews into product-relevant parameters that engineers can apply [72]. This tool was chosen because of its ability to improve the formulation of requirements lists through a better representation of customer requirements and identify critical product functions. This chapter will go through the process of turning the operator feedback from Chapter three into operator requirements. Then the operator requirements will be used to develop design requirements for a human-robot workstation that is able to fulfill the needs of production and provide comfort and acceptance to the operator. Meissner et al. emphasizes the importance of finding out what really matters to the workers because an HRC system might fulfill all theoretical guidelines but still not be accepted by operators [50].

#### **Customer Requirements**

Based on the results from the survey and the interview results from Chapter three, it is clear that one way to improve the interaction between operators and robots is to meet the operator's requirements for working in a collaborative setting. In order to identify the operator's requirements a Lean Six Sigma tool called Voice of the Customer (VOC) can be used. Lean Six Sigma is a disciplined, data-driven approach to eliminating defects and solving problems. Most of the techniques discussed in this chapter will be from techniques taught in the Lean Six Sigma Green Belt Training Guide by Michael Parker. VOC is a data-

driven plan to discover customer wants and needs. It can be done indirectly through warranty claims, customer complaints, service calls, or sales reports. It can also be done directly through conducting interviews and surveys, like the approach taken in this thesis. The direct method is more effective since there is less need to interpret meaning, the researcher has the ability to go deeper when interacting with customers, customers typically respond better, and researchers can properly plan the questions, sample size and information collecting techniques.

There were six questions during the survey and the interviews that allowed responders to voice their wants and needs for interacting with a robot. Table 7 contains the questions that generated the responses in Table 8. Between the interviews and the survey several comments were made as suggestions to improve comfort, acceptance, and the overall interaction between humans and robots in a workstation.

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Table 7: Questions asked to determine the wants and needs of the customer.

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What would help create a team-like experience between you and your robot?  
 If you could talk to the engineers who build the robots, what would you ask the engineers to build into the robot just for you?

How could working with a robot be more enjoyable?

What would make you feel challenged happy excited valuable and productive while working with a robot?

What would make you feel more comfortable and accepting of working with a robot?

What requirements would you have for working with a robot?

---

Table 8: Customer Feedback		
function correctly	safety	avoid injuring human
process everything properly	safe zone	automatic variable speed
accuracy	extensive training (for robot)	voice control
work correctly	extensive development (for robot)	speed control
function correctly	tested in different scenarios	adjust pace
less downtime	training system (for operator)	radio
don't cause downtime	safety procedure	tell jokes
no defective movements	sensitive to extra forces	health monitoring
do most of the tasks	working side by side	trainable
do all the heavy lifting	understanding how the robot works	learn different positions of the line
easier to fix	being able to maintain it	evidence that it will increase quality or production
communication	there for assistance	be helpful
be safe	training on the robot	more realistic implementation
working together to fulfil a purpose	user friendly	Variety in the job
learning about the robot	experience with the robot	complete control
teach pendant	HMI	safety barrier

The next step is to generate the CTQs or Critical to Quality. This is a way to translate the feedback into something meaningful. CTQs are typically quantifiable, measurable, and meaningful translations of VOC. One effective way to organize VOC is to group the feedback using an affinity diagram. An affinity diagram is typically used to organize a large number of ideas into subgroups with common themes or relationships. The affinity diagram makes it much easier to visualize the commonality and plan for and address the feedback from the survey and interviews. To build an affinity diagram first the question or focus must be defined. The focus is on requirements for improving operators experience working with robots. Then the responses are recorded on note cards or sticky notes and displayed on a wall if necessary. The next step is to look for and identify common themes within the responses and group the note cards into themes until all the responses

have been allocated. The final step is to re-evaluate and make final adjustments. The finalized affinity diagram can be seen in Table 9 and Table 10.

Table 9: First half of affinity diagram.

Make it Safe	Make it Enjoyable	Make it Controllable	Makes sure the robot is dependable	Make the experience value-adding
Safety	Tell Jokes	Complete control	No defective movements	Extensive development (for robot)
Be safe	Play radio	Speed control	Don't cause downtime	Working together to fulfil a purpose
Avoid injuring human	Variety in the job	Adjust pace	Function correctly	Extensive training (for robot)
Safe zone	Working side by side	Automatic variable speed	Process everything properly	More realistic implementation
Sensitive to extra force	Health monitoring	Voice control	Less downtime	Evidence that it will increase quality or production
Safety procedure			Function correctly	
Avoid injuring human			Accuracy	
			Function correctly	
			Work correctly	

Table 10: Second half of affinity diagram

Make it easy to fix	Make it easy to communicate with	Make it teachable	Make it helpful	Provide information about it
Easier to fix	User friendly	Trainable	Be helpful	Understanding how the robot works
Being able to maintain it	Human machine interface	Learn different positions of the line	Do all the heavy lifting	Learning about the robot
	Communication	Teach pendant	Do most of the tasks	Training on the robot
			There for assistance	Experience with the robot

To summarize, in order to improve the operator's experience working with the robot, the robot must be safe, dependable, easy to fix, easy to communicate with, teachable, controllable, and helpful. Furthermore, the interaction between the operator and the robot needs to be enjoyable and value-adding. Prior to the experience the operator also needs to fully understand the robot and have the proper training in order to feel comfortable. A total of ten CTQ topics have been developed from this affinity diagram.

To further categorize these CTQs another technique called Kano can be used. The Kano model was developed by Noriaki Kano in the 1980s. Kano is an approach used to prioritize the features of a product or service based on how customers view the features. The graphical tool divides requirements into three categories: must haves, performance attributes, and delighters. An illustration of the Kano Diagram can be found in Figure 10.

The three categories are basic needs which fall into the Kano's "must have" category, performance attributes which will distinguish the system from other products on the market and improve the product's performance in some way, and excitement which fall into the Kano's "delighters" category, whether they improve performance or not these are the requirements that generate excitement. "Must haves" are often taken for granted when they are present but if the "must haves" are missing then the operator will be dissatisfied. The delighters are the opposite of the must haves. They are a nice surprise to the operator if they are there but if the delighters are missing then the operator will not be dissatisfied. The performance attributes are the requirements that are expected and are necessary for satisfaction. In Table 11 the categorization of the CTQs for HRC can be found.

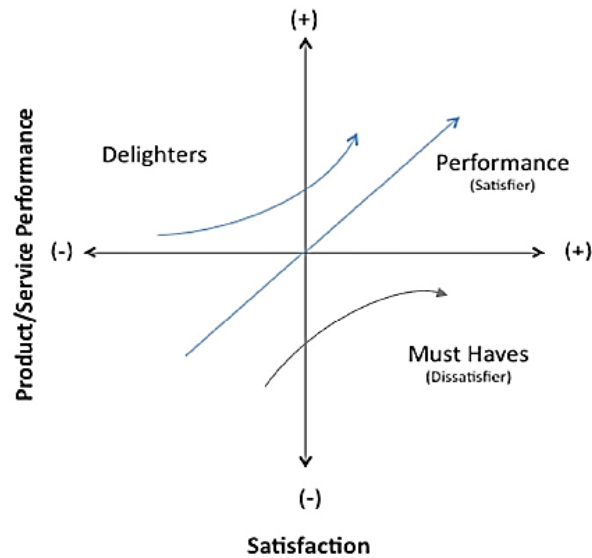


Figure 10: Kano Diagram from the Lean Six Sigma Green Belt Training Guide by Michael Parker

Table 11: Kano Categorization of CTQs

Delighters	Performance Attributes	Must haves
Make it enjoyable	Make it helpful	Make it Controllable
Make it easy to fix	Make it easy to communicate with	Make the experience value- adding
Make it teachable	Provide information about it	Make it safe
		Make sure the robot is dependable

The CTQs were categorized based on the amount of responses in each category of the affinity diagram in Table 9 and Table 10 and the assumptions made from the surveys and interviews. For example, enjoyable was placed into the delighters category because the suggestions found in that category such as telling jokes, health monitoring, and playing radio are extra features that would not normally be found in a human-robot workstation. Variety in the job and working side by side also may not be common in a typical workstation. While these features would be nice to have if they were missing it would not cause complete dissatisfaction with the workstation. The same can be said for easy to fix



and teachable. Ideally the robot would be programmed before the start of production and the operator would not need to program it. If the robot is reliable then it would not break down often enough to need to be fixed. If it were to break down, then there are technicians who would be able to fix the robot. Now that the CTQs have been identified and categorized they can be turned into requirements for the QFD process.

### **House of Quality**

The main working chart of QFD that contains the customer requirements is called the House of Quality. An example of it can be found in Figure 12. It takes seven steps to build a House of Quality:

1. Determine the Customer Requirements (“What’s” from VOC/CTQ)
2. Technical Specifications/Design Requirements (“How’s”)
3. Develop Relationship Matrix (“What’s” and “How’s”)
4. Prioritize Customer Requirements
5. Conduct Competitive Assessments
6. Develop Interrelationship (“How’s”)
7. Prioritize Design Requirements

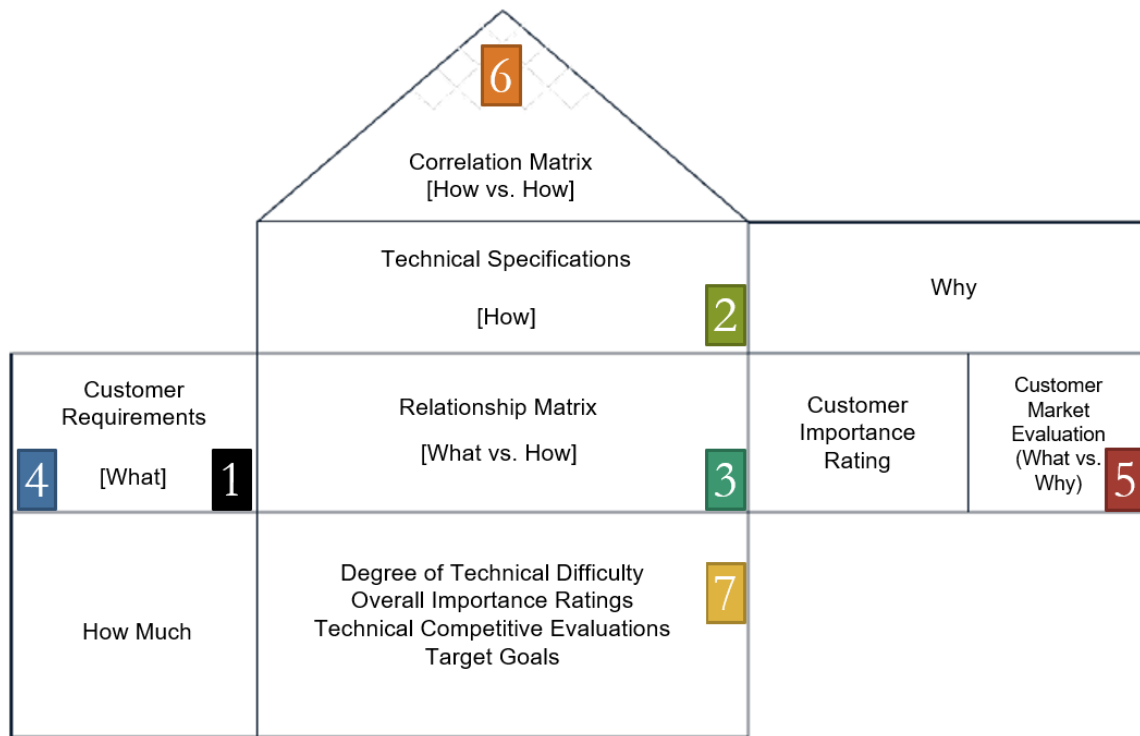


Figure 11: House of Quality example from the Lean Six Sigma Greenbelt Training Guide by Michael Parker

For the purpose of this thesis the fifth step of conducting competitive assessments will not be completed. The goal is to develop a general guide that can be applied to any human-robot workstation. Competing the House of Quality can be a very subjective process and can be hard to accomplish alone. In order to deal with the subjectivity, the responses from the interviews and surveys were referred to and the rankings were conducted with other peers to mitigate the bias that would come with doing the process alone.

In this section the author will go through the process of each step. First the customer requirements will be defined and prioritized. Then the design requirements will be defined along with how they impact customer requirements. This will be followed by a visual of

the relationship matrix for customer requirements and design requirements. After that the interrelationships of the design requirements will be illustrated. This will be followed by the importance rankings of the design requirements.

### *Determine Customer Requirements and Ranking*

As mentioned previously, the customer requirements are determined through the VOC and CTQ process. Using the results from the affinity diagram in Table 9 and Table 10, the nine customer requirements listed in Table 12 have been determined. Information about the robot is not captured in this table because it is a process that will most likely take place outside of the workstation. However, providing information about the robot to the operator is not a requirement that should be forgotten.

Table 12: List of Customer Requirements

Dependable	Controllable	Teachable
Safe	Helpful	Easy to Fix
Value-adding	Easy Communication	Enjoyable

The robot must be dependable. That means it should not cause downtime, it should function properly, and it should be not have issues completing tasks. The operator wants to be able to depend on the robot to do its share of the tasks in an accurate and efficient way. Otherwise, the robot will be seen as a burden instead of a valuable teammate. As Meissner et al. states, it does not make the operators happy when the robot cannot do what it is supposed to do [50].

The operator also wants to be able to control aspects of the robot. For example, the operator wants to be able to change the speed of the robot to match the operator's pace. The reason that it is important for the operator to have control is because taking control

away from operators may alienate them, causing damage to overall productivity [69]. Control will help the operator feel more comfortable. From the interviews it was determined that some people view more control as a way to mitigate safety risks. Many operators would prefer to at least have the option to make decisions and take control. Meissner also found there to be a great desire for autonomy and control among operators [50]. Fully giving the control over to the robot can make the operators feel anxious and like they are admitting that the robot is superior and could replace the operator.

The robot needs to be helpful in order to prove its worth to the operator. Furthermore, if the robot is not assisting the operator, then that means the robot could be working independently, which is not the best way to get the most benefit out of a human-robot team. The robot should be there to lighten the workload, improve ergonomics, and allow the operator more time to focus on value-adding tasks. In order to be helpful, the robot must meet the needs of the operator as well as production.

The requirement for enjoyability is focused on ensuring that the operator is happy to work with the robot. As mentioned before, enjoyment relates to acceptance. When relating it to production this could be ensuring that the operator has an enjoyable role or receives an award for reaching a certain goal. For example, two of the feedback response state that the robot should be able to tell jokes or play the radio. Perhaps telling jokes and playing music could be implemented as a reward after hitting a target in production. Enjoyability can also relate to the ability to monitor the operator's health. Although this seems completely unrelated to production, monitoring the health or physiological signs of the operator could be used to measure signs of fatigue in which case the operator could be

told to take a break or slow down or the robot could be signaled to take some of the load off of the operator [73].

The teachable requirement would allow the operator to be able to train the robot. The operator would prefer to train the robot with a user-friendly interface. Sometimes the operator may notice that the robot could do things in a different way that would improve production. If this is the case, then the operator should be able to make this modification, given the appropriate restrictions. However, in most cases this job may fall to the engineering or manager to ensure that changes made to the robot will not negatively impact production.

Safety is an extremely important aspect of human-robot collaboration and is seen as a basic requirement. The objective of a collaborative working environment is to create a comfortable environment for human and robot interaction, where the task of the robot is to help and assist in achieving a goal. Of course, having the operator and robot work together can lead to safety concerns. The operator wants to know that it will not be in danger of being injured while working with the robot. The technical specifications for safety in HRC require safety-rated monitored stops, hand guiding abilities, speed and separation monitoring, and power and force limiting. Special attention should also be given to the distance between the operator and the robot, the trajectory of the robot, the speed of the robot, and the psycho-physiological state of an operator in order to reduce risks of hazard from the robot [74]. To reduce risk of hazard from the process, special attention has to be paid to the duration of the process and transitions between actions, lack of ergonomic solutions, the complexity of the task, and operator influence. Lastly, there is the risk of

hazard from the robot control system malfunction which includes paying attention to error of the operator, obstacles for the function of the robot's sensors, and malfunction at the control level. In order to maintain a safe and effective interaction between a human and a robot it is crucial to consider a complex task with a multitude of factors influencing the performance of production tasks.

Value adding of a robot is an operator requirement that relates to perceived usefulness which is one of the keys to operator acceptance of HRC [54]. Perceived usefulness is the degree to which an operator believes that using the robot will enhance his or her job performance and therefore be value adding. It is insurance that the robot will have a purpose and will not be added to the line just because it sounds like a good idea. The operator wants evidence that the addition of a robot will increase quality or production. Therefore, the robot needs to add value to the workstation.

The operator also has a desire to be able to communicate with the robot. This includes giving instructions and receiving feedback. Communication is an important aspect of any team and should be incorporated with human-robot teams as well. During the interviews many participants voiced the desire to be able to know what the robot was doing at all times. Communication is also important for safety. The operator needs to be able to tell the robot to stop if there is a risk for collision.

Lastly, some operators desired for the robot to be easy to fix. Since the goal here is to design a workstation and not to build a robot this may be a hard requirement to meet. The best way to satisfy this requirement will be to focus on providing the operator with the information they may need to understand why a failure is occurring and a possible solution

to fix it. Operators must be empowered and in control. If something goes wrong the operator should be able to fix it or at the very least be involved. This will allow them to understand the source of these events and possible outcomes which will help them to form an accurate mental model of the robot. The operator will also be in a position to identify factors that diminish or enhance the robot's ability to perform and be able to detect cues of potential malfunctions. Furthermore, if the operator is not involved, they are likely to feel alienated from the system which would lead to an incomplete mental model since the operator would not be able to develop an in-depth understanding of the system's source of failure [57].

Discussed in detail above, the ranking of the operator requirements in Figure 13 was done based on the frequency of results in each category of the affinity diagram in Figure 10 and the Kano categorization of the CTQs in Table 9 and Table 10.

1: low, 5: high	→
Customer importance rating	Customer Requirements - (What) ↓
5	Dependable
5	Safe
5	Value-adding
4	Controllable
4	Helpful
3	Easy communication
2	Teachable
2	Easy to fix
1	Enjoyable

Figure 12: Operator requirements ranking from House of Quality

### *Design requirements*

With the operator requirements defined, the next step in the process is to determine how the operator requirements can be achieved. When developing the design requirements, it is important to keep in mind the objectives that the intended solution is expected to satisfy. In this case the human-robot workstation is expected to bring comfort and acceptance to the operator and satisfy the need for production. In order to achieve this objective, ten design requirements have been selected and placed into Table 13. These design requirements were selected based on their ability to fulfil the operator's requirements

Table 13: Design requirements for a human-robot workstation

Quality Control	Proof of Improvement
Ability to work around robot	Efficient Workstation Layout
Good task allocation	Information flow
User controlled preferences	Efficient human-robot interface
User Engagement	Ability to handle variation



The design requirement for quality control can be quantified by the Six Sigma standard three parts per million. That means that for every million parts there are only three defective components that do not meet standards for selling. The purpose of this requirement is to ensure that mistakes in production are minimized. If mistakes occur frequently within a human-robot workstation then this can reduce the operator's faith in the abilities of the collaboration. As the participants from the interview mentioned, no one wants to work with a robot that is constantly making mistakes. Ensuring there is quality control within the workstation will help with reducing robot mistakes. An example of quality control is using a validation system that checks for errors or a Poka-Yoke system. Poka-Yoke systems are common applications that are designed to either notify the user when they have made a mistake or designed to prevent the user from being able to make a mistake [75]. A simple example of a Poka-Yoke is the cap to the gas tank of a car, which is attached by a string. It was not always designed like this, but after many people forgot their gas tank cap on the top of their car, someone thought of a way to prevent this from happening.

The ability to work around the robot is a design requirement that is in place to ensure that the operator can still perform tasks if the robot breaks down. If the robot is unable to function the operator will not be happy. However, they will have less of a negative attitude about it if they can at least continue with production. This is also beneficial to the company. They will have the knowledge that even though the robot is down for the day production can still go on. The structural design of the workstation will

heavily impact the ability to work around the robot. An adaptable structural design would lead itself well to being able to work around the robot.

Good task allocation is a requirement set to ensure that the workload between the human and the robot is divided in an efficient and beneficial way. This will impact the perception of how helpful the robot is to the operator. It will also impact the perception of how dependable and value-adding the robot is to the process. The tasks should be distributed based on skills. The robot should be focused on the repetitive tasks and the heavy lifting while the human should be focused on the tasks that require more thinking.

User controlled preferences allow the operator to set preferences that will help them feel more comfortable while interacting with the robot. For example, the operator may want to control the speed so that the robot is not going too fast or too slow. The user-controlled preferences also allow the operator to have some control over the system. As it was discussed in previous chapters, having control is very important to the operator. It can make them feel safer and more involved with the process.

User engagement is a requirement that ensures the operator will still have a purpose within the workstation. It also ensures that the operator will be more aware of what is going on in the workstation instead of working mindlessly. A lack of situational awareness can lead to safety issues. Furthermore, keeping the operator engaged could lead to the operator finding enjoyment while working in the station.

Proof of improvement is a requirement that focuses on making sure there is a way for the operator to know that the workstation is improving quality and production. This way the operator knows that the robot serves a purpose, and it was not something that was

purchased impulsively. Proof of improvement can be done with end of shift reports that let the operator know how they have improved on a daily or weekly basis.

Efficient workstation layout is a requirement that ensures that the workstation is organized in a way to promote production and human-robot interaction. The robot has access to everything it needs to complete its tasks, and so does the operator. More importantly they both have access to each other for collaborating.

Information flow is a crucial requirement. It involves the flow of information throughout the entire workstation. This includes ensuring all sensors necessary for production, safety, and human-robot interaction are present within the station. For example, if there is a sensor that dictates the point where the robot cannot cross then the information flow would be what tells the robot to stop when the sensor is crossed. Information flow would also tell the robot and the human the production plans for the day and ensure the notification from the validation system if something goes wrong.

An efficient human-robot interface includes the ability to communicate with the robot and the robot to be able to give the operator feedback. This allows for exchange in commands and status updates. An intuitive HMI could be used for this interaction.

The ability to handle variations is important so that if there is a change in production the company is not forced to buy a new robot. This requirement could be fulfilled by ensuring that all the tools and fixtures needed for production are in the workstation. Having an adaptable workstation also helps with dealing with variation in production.

### *Relationship Matrix*

Now that the design requirements and the operator requirements are fully defined it is important to determine the relationship between the two. In the portion of the QFD diagram in Figure 13 a weight of 1-3-9 was used to dictate weak, medium and strong relationships. These numbers will be used to help determine the importance ratings of the design requirements. This method of weighing the relationship between the operator requirements and the design requirements is what makes the QFD very subjective and a slightly mathematically inconsistent. There is no mathematical calculation to the ranking, it is done based on the perceptions of the individuals completing the process. The results from the ranking are taken and put into mathematical calculations that determine the weight and ranking of the requirements. If three diverse groups of people completed this process, each group could end up with different rankings because of the way this process works. That is why it is important to complete this process with everyone involved in the workstation across multiple departments to mitigate the bias.

Functional Requirements (How) → Customer Requirements - (What) ↓	Quality Control	Ability to work around robot	Good task allocation	User controlled preferences	User Engagement	Proof of improvement	Efficient Workstation Layout	Information flow	Efficient human-robot interface	Ability to handle variation
Dependable	9	3	9				3	3	9	9
Safe		3					3	9	3	
Value-adding	3		9	1	3	9	9			9
Controllable				9	9			3	3	
Helpful	3		9	1	9	3	3	1	1	9
Easy communication				3	9		1	9	9	
Teachable					3			3	9	1
Easy to fix					1		3	3	3	
Enjoyable			1	9	9	3		1	3	

Figure 13: Relationship Matrix

### *Interrelationship of Design Requirements*

In Figure 14 an image of the roof of the house shows the correlation matrix between the different design requirements. The only design requirements with a negative correlation are good task allocation and user-controlled preferences. This is to highlight the need for restricted user-controlled preferences in order to ensure efficiency is not negatively impacted.

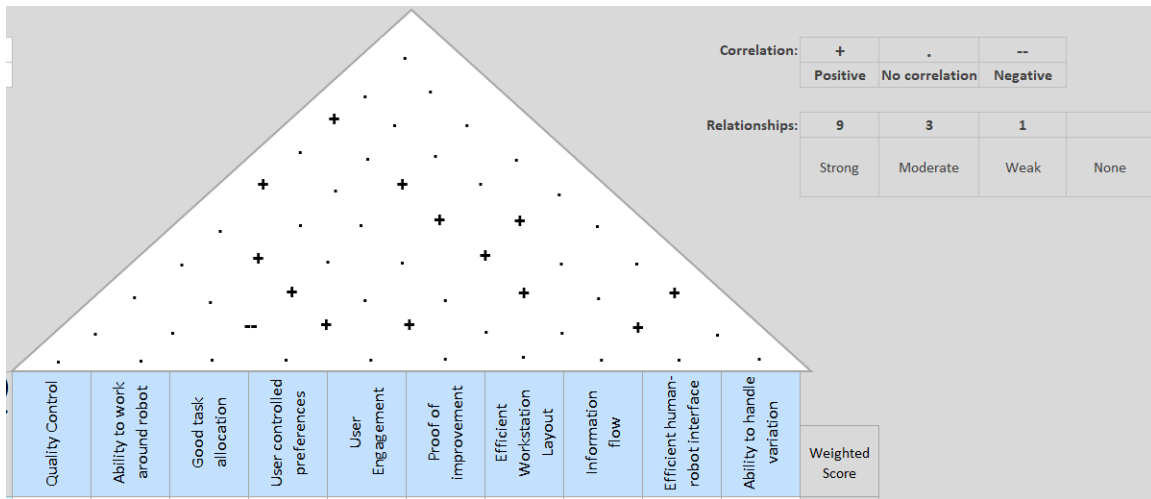


Figure 14: Correlation Matrix

### *Prioritize Design Requirements*

Now that the House of Quality has been completed, the results are a prioritized list of functional requirements. In the table below the ranking is shown. Now that the requirements for the workstation have been determined it is time to break the requirements down into their subsystems and apply them to a case study.

Table 14: Prioritized Design Requirements

Design Requirement	Ranking
Good Task Allocation	1
User Engagement	2
Efficient Human-Robot interface	3
Ability to Handle Variation	4
Information Flow	5
Efficient Workstation Layout	6
Quality Control	7
User Controlled Preferences	8
Proof of Improvement	9
Ability to Work Around Robot	10

## CHAPTER FIVE

### CASE STUDY

The objective of this chapter is to apply the findings from Chapter four to a real-world industry project given by the same company that provided the survey participants. The project was assigned to eight students in an intercollegiate graduate class including the author who acted as project manager. The other participants names are Lauren Mims, Geoff Musick, Nirali Bandaru, Jacqueline Burrows, Steven Andrews, Rohan Jain, and Dustin Conley. In order to tackle the project, the group was divided into sub teams. The project was not a fully collaborative workstation, but there was still an opportunity to apply the concepts from the thesis to the project. The discussion in this chapter will be focused on defining the subsystem requirements, identifying how they were applied, and describing how they relate to the operator's requirements.

#### **The Project**

A company is interested in developing a human-robot workstation in order to replace a process that is currently being outsourced by a third-party. The company is in the industrial machinery and equipment merchant wholesaler's division. The company primarily engages in merchant wholesale distribution of specialized machinery, equipment, and related parts generally used in manufacturing. The creation of this workstation would ideally reduce lead time for orders and save money. The company would no longer have to worry about the time it would take the orders to arrive in house nor would they have to spend time auditing the delivery. The reason that the company would like to use a human-

robot workstation is because it provides a balance between a manual process and a fully automated process. A manual process may lead to a longer takt time and cause a human operator to do repetitive non-value adding tasks, while a fully automated system would be costly. The human element is a vital part of the production chain due to the fact that a significant amount of assembly work still requires the flexibility of an operator [57]. This workstation contains a lot of part variation, that an operator would be able to help with. Meissner states that human-robot collaboration can provide major advantages compared to manual assembly and full automation; however, it can only be successful if the workforce is willing to accept it [50].

This acceptance can be achieved through the use of the design requirements generated with the operator requirements. In order to apply the design requirements generated in Chapter four the workstation should be broken down into subsystems. These subsystems can include areas such as: the structure, the robot, the control system, the sensor system, and the validation system. For this case study only three of these subsystems will be discussed, the robot, the validation system, and the structure. The three subsystems are labeled in Figure 15.



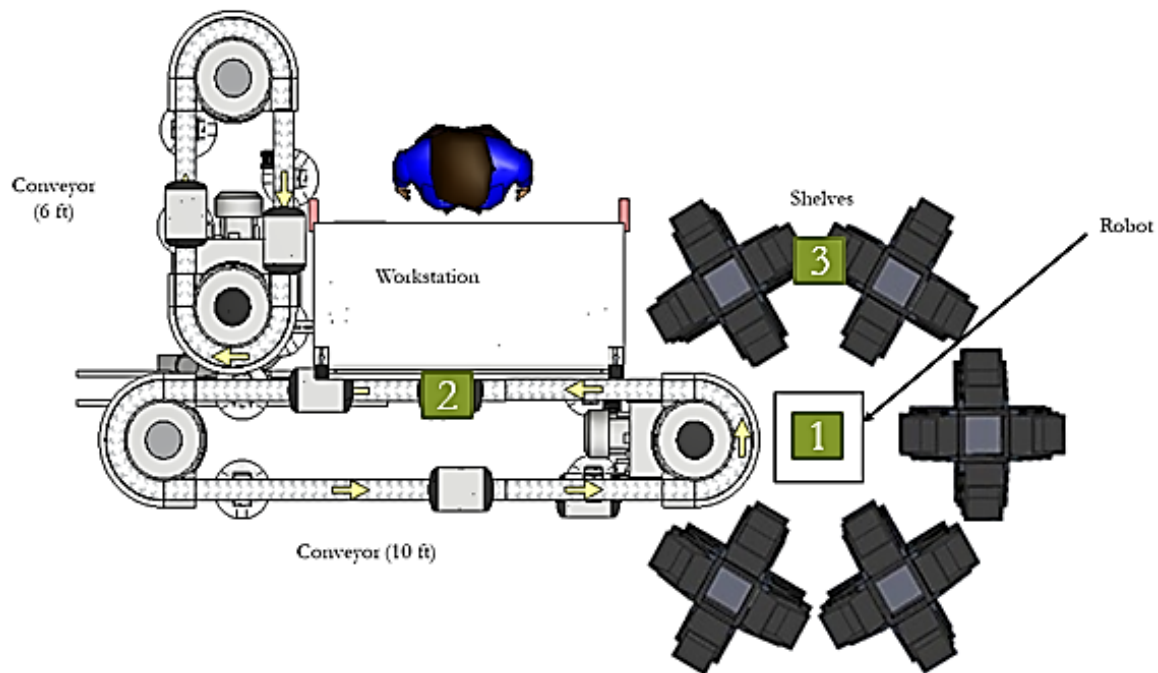


Figure 15: Model of prototype kitting workstation layout including the Robot (1), the Validation System (2), and the Structure (3)

The product that this workstation would be producing are kitting orders. These kits contain material such as screws, bolts, nuts, and gussets that can be used with aluminum extrusion to build workstations, fixtures, or anything else a customer wants to build. The kits are typically sold to manufacturing companies that need to build equipment for production. Each kit contains up to six different components and each order can contain up to three hundred identical kits. There are thirty-eight unique components and twenty-six unique kits. The workstation designed must be able to handle the current variation in components and be scalable and flexible for the potential development of more components.

## **Robot Subsystem**

### *System Requirements*

In Table 15 the robot system requirements are listed. The QFD for the robot subsystem can be found in the Appendix. In order to meet the design requirements discussed in Chapter four, ten system requirements were determined for the robot. Safety is the top priority when working with collaborative robots. This ensures that the operator will be safe while interacting with the robot. Vision capabilities are necessary to help the robot become more aware of the environment around them, especially when it comes to picking up objects. Grasping capabilities are also crucial when it comes to picking up objects. Grasping capabilities heavily relates to ensuring that an appropriate end effector is selected. The ability to provide feedback ensures that the robot will be capable of communicating with the human. Interruptible is defined as the operator's ability to intervene when something goes wrong. Intervention refers to the ability of the operator to stop the robot mid-process. This is crucial for moments where the robot may start to follow a command with unintended consequences. As it is mentioned by Peter Fröhlich et al. when a system is running flawlessly the ability to interrupt the system is not necessary [76]. However, if an issue occurs the operator must be able to intervene and do it quickly. This is crucial for safety and can also help with preventing the robot from making mistakes. Schmidt et al. have introduced the idea of intervention user interfaces for automation and the same concept can be used for HRC [77].

Table 15: Robot System Requirements

Safe	Receive Information	Adaptable
Vision Capabilities	Easy to use	Interruptible
Grasping Capabilities	Controllable	Teachable
Provide Feedback		

### *Case Study Example*

Figure 16 contains an image of a robot attempting to pick up parts and place them into a cardboard box. For the case study a UR3 robot was selected for initial prototyping. A UR3 robot is one of the robots designed by Universal Robots. This robot's design meets the requirements for safe, easy to use, teachable, adaptable, interruptible, ability to receive information, ability to provide feedback and controllable. It has a very user-friendly interface that would allow any operator to make it operational in less than half a day. It primarily receives information and provides feedback through the teach pendant. Using the teach pendant the operator has the ability to see where the robot is in the program at any given moment. Furthermore, through this teach pendant the operator can program the robot to do anything and control the speed. If desired the operator could manually move the robot to the right positions which can be stored and adjusted using the teach pendant navigation keys. It is also possible to control the safety parameters. For example, if the robot runs into anything with enough resistance the robot will force stop and the operator can control the settings for the safety stopping force. It is also possible to set up safety sensors and safety barriers.

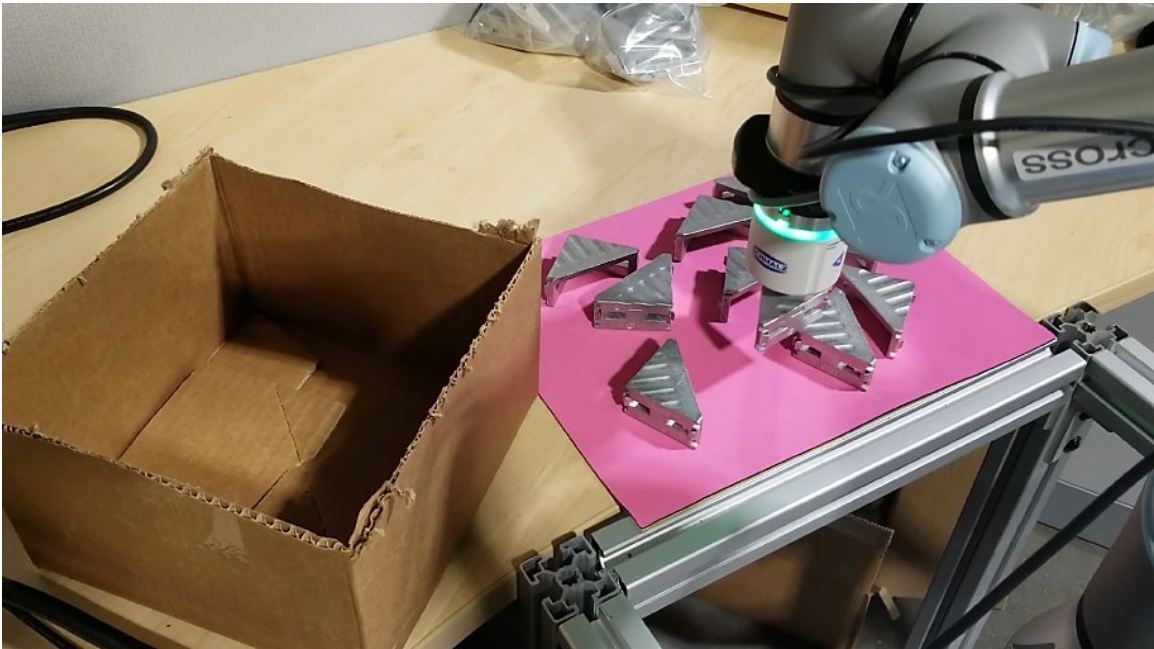


Figure 16: Prototyping of the picking and placing operation.

Surprisingly, the most challenging part of working with the robot was meeting the vision and grasping capabilities. Since the kitting process handles a variety of components it was harder to meet the requirement for the robot to have the appropriate grasping capabilities that would work with all of the components. Additionally, since the target is to pick the parts out of bins this makes it harder to meet the requirements for the vision capabilities. Since the parts are not placed in front of the robot systematically the robot needs to be able to see where the components are and pick them up. The two options were to use a very expensive 3D picking system that has the ability to pick directly from the tote or use a 2D vision picking system that requires components to be on a flat surface. Currently the 2D vision picking system is being implemented with the use of a wrist camera. With the vision capability requirement fulfilled an end effector needed to be

selected to fulfill the grasping capabilities. The solution was to find an end effector that would be able to work for a variety of components or develop an end effector with multiple options for picking that the robot could rotate through. A variety of end effectors had to be tested in order to determine which one would be the most efficient at providing the robot with grasping capabilities. The selected end effector has the ability to pick up the parts by using suction. This suction end effector had the ability to pick up most of the components, except for the ones that were too small. In order to compensate for the robot's inability to fully meet the design requirement the team had to look into a dispensing alternative.

The way that the subsystem works is that the wrist camera takes a snapshot to identify viable candidate(s) to be picked. Then the coordinates are provided to the UR3 system for the next picking operator. The system then combines the relative position of the next pick with the current program/function in order to incorporate the target's position into the process. This means that the robot movements are based on the relative X-axis and Y-axis position of the target and the Z-axis component of the function stays constant. Once the program runs the robot picks up the part. The process can be done for one component each time, requiring the camera to take a new picture after each pick or the robot can repeat the process for every piece identified until none remain from the original picture. Taking less pictures would make the process go faster but it would only be beneficial if the environment is controlled, ensuring that the components would not move between picking components.

### *Summary*

The major design requirements fulfilled through the robot are good task allocation, ability to handle variation, and efficient human robot interface. This was done through the selection of the robot and fulfilling the subsystem requirements of grasping capabilities and vision capabilities. Ensuring that the robot has the best grasping capabilities and vision capabilities to fulfil the job helps to fulfil the operator's requirement of dependability and gives the robot the ability to meet the operators needs and contribute to the team. Ensuring that a user-friendly robot is selected such as the UR3 helps to fulfill several of the subsystem requirements as well as the operator requirements for a safe, controllable, and helpful robot that is easy to communicate with and teachable.

### **Validation Subsystem**

#### *System Requirements*

In Table 16 the validation system requirements are listed. The QFD for the validation system can be found in the Appendix. In order to meet the design requirements discussed in Chapter four, six system requirements were determined for the validation system. The ability for the validation to store information is crucial. This is what the validation system pulls from in order to check if there is an error. The error tracking system requirement helps to keep track of mistakes made in production, which allows for the possibility to track mistakes and determine their cause and how to prevent them in the future. If errors occur frequently this would be a sign that the engineer would need to take a closer look at the process and make improvements. The notification system is what would notify the operator that a mistake has been made in which case the operator would perform

a correction procedure. The system could also be set up to let the operator know they are about to make a mistake; in which case a prevention procedure would take place. The requirements of a prevention procedure and a correction procedure have a negative correlation since only one of the procedures can take place. The vision capability requirement is also crucial to the validation system. Otherwise the system would not be able to detect if a mistake has been made.

Table 16: Validation System Requirements

Vision Capabilities	Notification System	Prevention Procedures
Correction Procedures	Error Tracking System	Information Storage

### *Case Study Example*

Figure 17 contains an image of the validation system identifying parts placed into a tray. In order to fulfill the subsystem requirements for the validation system a Pi camera was selected for the vision capabilities and YOLO was selected to handle information storage. YOLO is an object detection algorithm that uses deep learning to train image datasets and classify detected objects in images, videos, or real time video streaming with a reasonable balance between classification accuracy and computation time [78], [79]. The notification system is implemented through the use of a light system. A mistake is represented by a red light, a successful kitting process is represented by a green light, and when the validation system is in progress the light is yellow. The error tracking requirement is fulfilled with the use of a counter that keeps track of when the validation system identifies a component is missing or the wrong component has been placed. For the kitting workstation the requirement for a correction procedure is fulfilled instead of a prevention

procedure. Ideally the robot would not forget to place a component or select an incorrect component but if the robot does the operator will fix the kit.

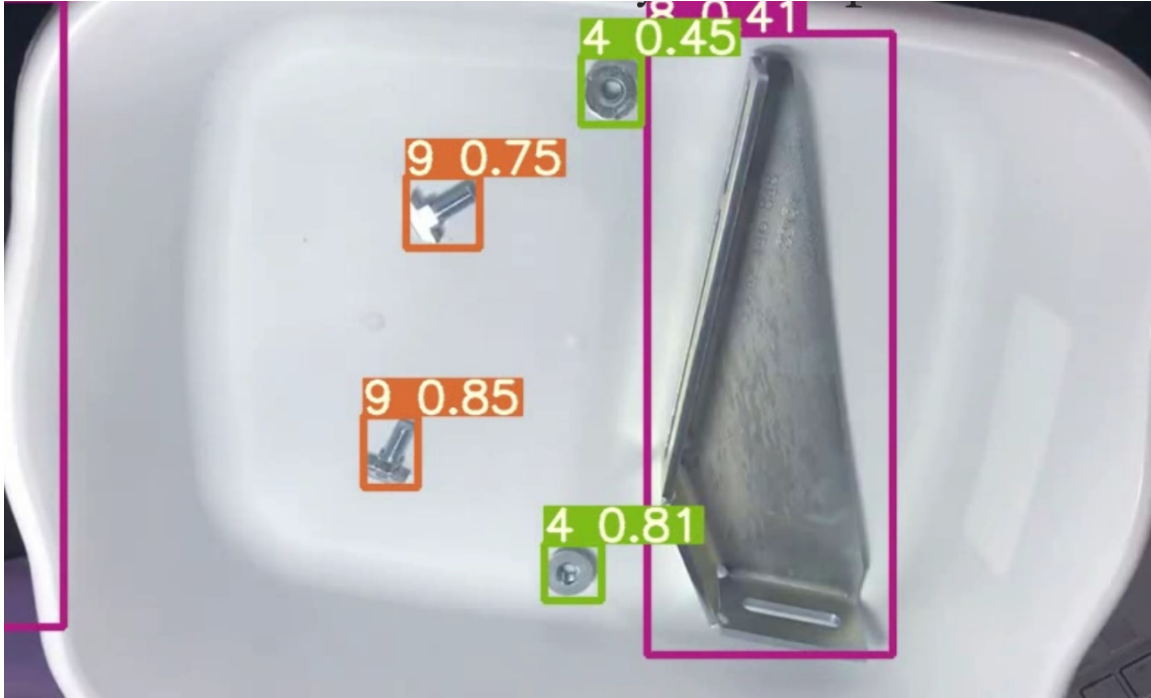


Figure 17: Prototyping of the Validation System

The machine vision-driven validation system seen in Figure 17 uses the YOLOv5 object detection algorithm to detect parts from an input video. The image dataset used to train the model consists of more than 5000 images of parts from kits used for testing. Images of parts were taken from different angles and orientations, and more images were generated by manipulating the original images (tilting, rotating, changing brightness and hue, and converting to greyscale). The best weights from the trained model are used to classify the detected objects and a confidence value is calculated for each classification, as shown in Figure 17. The confidence value changes with each passing frame in the input



video. The trained model is deployed onto the Raspberry Pi embedded board and the Pi camera is used to process real time video footage to classify detected objects.

### *Summary*

The major requirements fulfilled through the validation system are quality and proof of improvement. This is done through fulfilling the subsystem requirements of vision capabilities, correction procedure, and error tracking system. Having the system feed information into a proof of improvement system that provides the operator with updates allows for the operator to see how valuable and helpful the robot is assuming that the robot's involvement leads to improved quality in the process.

## **Structure Subsystem**

### *System Requirements*

In Table 17 the structure system requirements are listed. The QFD for the structure system can be found in the Appendix. In order to meet the design requirements discussed in Chapter four, ten system requirements were determined for the structure. The structure must be strong, and it must be stable. Strength and stability ensure that the structure can hold weight and will not collapse in a way that could harm the operator. The requirement for safety is also achieved with strength and stability. Safety also includes ensuring the structure does not have any sharp edges or pose any threat to the operator. The structure must also be ergonomic. If the operator has to interact with the structure it has to meet, he appropriate ergonomic requirements such as an ideal reaching height of thirty inches. The structure should also be accessible. Accessibility includes the ability for the operator and the robot to have access to anything needed for production. Having an organized structure

also ensures that the operator and the robot can easily find any need tools or components. Storage capabilities refers to the structures ability to hold all necessary materials for production. Having storage capabilities limits the amount of time the operator must spend away from the workstation gathering material. The requirement of adaptability means that the structure can adapt to changes in production. Longevity and easy maintenance go hand in hand to make sure the structure is designed to last for a long time.

Table 17: Structure System Requirements

Strength	Adaptable	Ergonomic
Safe	Organized	Accessible
Storage Capabilities	Stable	Longevity
Easy to Maintain		

### *Case Study Example*

Figure 18 contains an image of the structure that is designed to hold eight different components in bins for the robot to pick from. In order to fulfill the subsystem requirements for the structure strong material was selected for the strength requirement and gussets with screws and bolts were attached to help with the stability. Part of the structure involves two turntables that allow for the two levels to rotate independently. This design feature had a negative impact on the stability of the structure but was fixed by increasing the size of the turntables. The idea was to have five of these structures surrounding the robot to ensure storage capabilities. Each structure can hold eight totes which means that all five structures would be able to hold forty totes. Since there are thirty-eight different components this allows for all the components to fit around the robot. At one time ten of the components will be facing the robot. The structure also has the ability to rotate in order to meet the

accessibility requirement. If the ten components that are facing the robot do not meet the needs of production, then the structure can change to allow the correct set of components to face the robot. The ergonomic requirement was one of the more difficult requirements to meet. Since the ideal reaching height for an operator is thirty inches and the structure has two levels that means that the bottom level has to be no less than eighteen inches off of the ground and the top level has to be no higher than forty two inches off of the ground. In order to meet the organization requirement, once each bin has a designated spot labels will be added to the structure so that the operator knows where each component goes. The structure is built into three different sections: the base, the bottom level, and the top level. The three different sections are easy to take apart making it easy to maintain if parts need to be switched out in one section. Based on the design it is also assumed that the structure meets safety and longevity requirements.

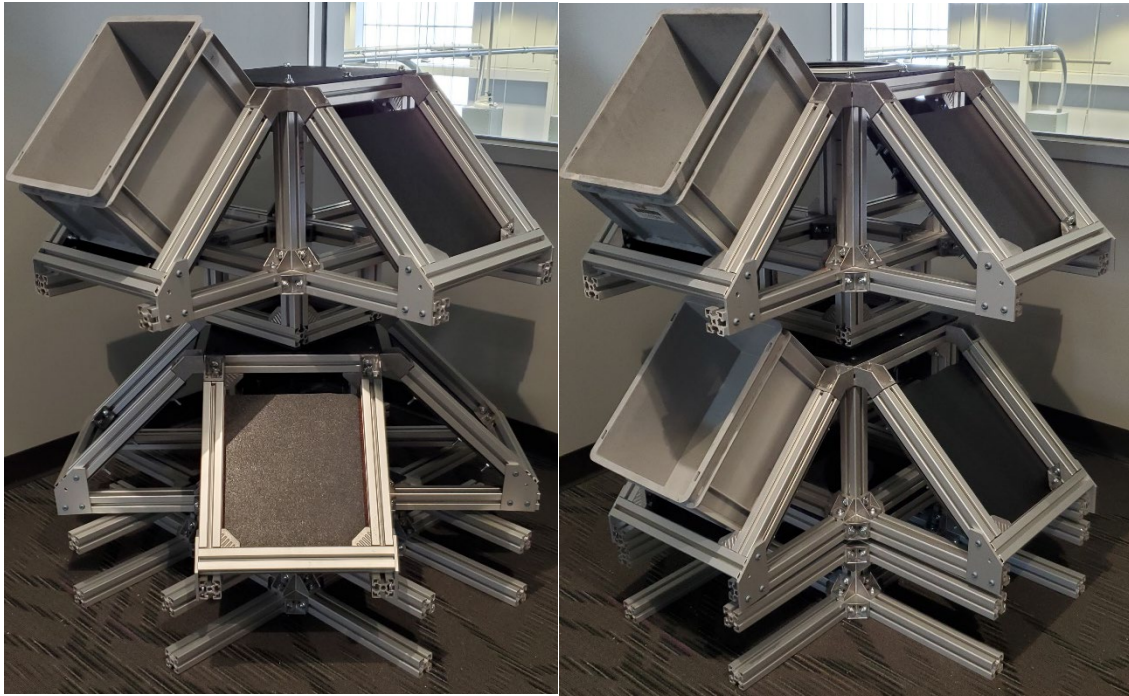


Figure 18: Prototyping of the Structure System

The structure can function manually or automatically. In a manual setting the operator would be notified about which bins are needed for production. Then the operator will make sure that the bins are rotated toward the robot. When a bin becomes empty the operator will be notified and will rotate the structure to remove the empty bin and replace it with a new one. If the structure is automated then the job of the operator will only be to remove empty bins and refill them since the structure will be able to rotate on its own when it is time to restock or there is a change in production.

### *Summary*

The major requirements fulfilled through the structure are an efficient workstation layout and the ability to work around the robot. This is done through fulfilling the subsystem requirements of storage capabilities, ergonomics, and accessibility. With the

arrangement of the shelves if the robot were to breakdown then the human would still be able to access the bins. Ergonomics was an especially important requirement to meet when it comes to the height of the shelves since the operator will have to place thirty-pound totes on to each level. Since the five-piece structure has the ability to hold forty totes it allows for the operator to spend more time on their tasks instead of swapping out material for the robot.

### Combined Weighted Score

Independently the subsystems may not meet all the design requirements however, in Table 18 it is clear that when combined the subsystems have the ability to contribute to all of the design requirements. In the next chapter the design requirement of user-controlled preferences will be further discussed.

Table 18: Combined weighted score of the robot, structure, and validation subsystems.

Design Requirements	Combined Weighted Score
Information flow	180
Quality	264
Good task allocation	240
Ability to handle variation	292
Ability to work around robot	99
User controlled preferences	120
Proof of Improvement	48
Efficient Workstation Layout	180
User Engagement	79
Efficient human-robot interface	66

## CHAPTER SIX

### USER-CONTROLLED PREFERENCES

The contents of this chapter are theoretical in nature. In Chapter four user-controlled preferences were listed as one of the design requirements for a workstation. In Chapter three the concept of finding a balance between satisfying the operator and satisfying the needs of production was mentioned due to the interview discussions on controllable preferences. User-controlled preferences could be key in allowing operators to find comfort in a human-robot workstation. User-controlled preferences could also be used to strengthen the shared mental model between the operator and the robot. The operator's ability to control the settings within the robot will inevitably impact production. The user-controlled preferences design requirement should be applied in a way that increases productivity, efficiency, and the teamwork between operators and robots. The objective of this chapter is to discuss the approach, concerns and benefits that could come from user-controlled preferences.

#### **Approach**

Based on the background research done in Chapter two and the results in Chapter three, operators desire to have control. User-controlled preferences is a way of giving operators some control in their mandatory interactions with robots. The idea behind user-controlled preferences stems from the current state of adaptive robots. These robots learn over time how best to meet the needs of the operator. Instead of trying to learn over time, user-controlled preferences give the robot the ability to start off with knowledge about the

operator. The idea is to use an interactive profile as a format for the operators to set their preferences. As the operator puts information in, they would simultaneously learn about the robot's capabilities. This allows the operator to learn more about the robot's capabilities and know that the robot is trying its best to be a good teammate and meet the operator's needs. This allows for the development of a shared mental model from day one. This system could potentially improve comfort, promote acceptance, and improve efficiency.

The preferences that could be provided to operators as options to control depend on the functionality of the workstation. Wang et al. found that factors impacting the operator's comfort the most include robot response speed, the robot movement trajectory, the human-robot proximity, the robot object manipulating fluency, human coding efforts, the robot sociability, and factors outside human-robot teams [49]. Other options for the operator to control include work style preferences, communication preferences, and part positioning height.

### **Mitigating Concerns**

The major concern for user-controlled preferences are the impact that they can have on efficiency, which was discussed in Chapter three. One of the concerns about user-controlled preferences is the deviations that it could cause in production. However, one could argue that adaptive preferences could cause the same problem. In both situations the robot is adapting to the user. One is instantaneous and one is over a period of time, but the controlled preferences and adaptive preferences both do the same thing. The only difference is that in one case scenario the human is inputting the preferences while in the other an algorithm is making observations and calculations to determine how best to adapt

to the operator. If each operator in the plant has a different method for working, then each adaptive robot could function differently as well, creating deviations in production. One advantage of user-controlled preferences is that parameters could be set so that the preferences stay within a certain range to mitigate the deviations. Furthermore, once settings are put in place the robot would consistently act the same way until the settings are changed again. For example, if the settings stay the same for three months then the robot will perform the same way every day for three months. However, the adaptive robot may have slight changes in performance over that time period since it is constantly trying to adapt to the operator.

Another concern is that the efficiency and takt time of production would be negatively impacted by the operator, but that does not have to be the case. Engineers and managers who have done the research and time studies can set the restrictions for the user-controlled preferences to ensure that no matter what the operator selects they cannot cause major issues. This would require more work on the part of management, but it may be worth it to be able to provide efficient production and comfort to operators. This would also ensure that the robot is not too easy to control and manipulate. There is another concern about it being difficult to trace back an issue in production because of deviations. Assuming the company can track the defect back to the workstation they would be able to access the user-control preferences and determine what the settings were when things went wrong in production.

Lastly, there is a concern about the ability of the operator to truly know what their preferences are. Mitsunaga et al. conducted a study and found that it can be very difficult



to measure true preferences [66]. Sometimes an operator's stated preference may not match up with their preferences during the interaction. The benefit of having a profile for each operator is that the operator would be able to go back into the system and make modifications to their preferences. The same solution can be used if the preferences an operator has on the first day changes six months later.

### **Hypothetical Application Example**

An example of applying user-controlled preferences to the kitting workstation case study described in Chapter five, would be controlling the robot speed. Based on the interview responses in Table 18 it is clear that the ideal working style for the kitting workstation would be to divide and conquer. The robot would be picking the parts and the operator would be assisting with packaging while ensuring the station remains stocked. As mentioned in Chapter three, working at the same pace is important to ensure the robot does not overproduce and the operator does not have to wait on the robot. The operator would set the speed in order to help the robot match the pace of the operator. Since the restrictions would have been set by management, no matter how slow the operator sets the speed to be the speed will be acceptable for production. Reversely, to ensure safety, the operator would not be able to make the robot work faster than a predetermined safe speed.

Table 19: Responses from interview about work preferences in a kitting workstation.

Response 1	Response 2	Response 3	Response 4	Response 5
Divide and conquer on picking and placing	The robot could pick parts and I could get things ready and keep him supplied	The robot would pick and place and the human would be in charge of refilling	The robots picking and I'm packing	Make sure the robot has enough supply and make sure all components are in the kit

The operator could also have the option to control the communication style of the robot. In this case, the operator would determine whether they would like to be notified by a light or by sound. A manufacturing facility can be very loud, but since the notification would not be verbal, it may still be possible to understand the notification. There could be a loud angry buzz for errors and a celebration horn for a successfully completed kit. It would be up to the operator's preferences. The operator could feel like it would be better to have the light notification because they do not have good hearing, or maybe the operator feels like the light is not always in their line of sight and the sound would catch their attention sooner. Thanks to the user-controlled preferences the operator can pick the option that works best for them.

## **Summary**

The user-controlled preferences could be worth further investigation. Unlike adaptive robots' interactive user-controlled preferences offer the user the ability to learn more about the robot and feel as if they have direct control of the HRC interaction. Having more control and a shared mental model are a couple key factors in promoting comfort and acceptance within human-robot interaction based on the research done in this thesis. If the operator is unable to select the correct preferences on the first try it still forces the operator to be a more involved and a self-aware, since they now play a role in being able to improve their interaction with the robot.

## CHAPTER SEVEN

### CONCLUSION AND FUTURE WORK

The goal of this thesis was to determine the design requirements for a human-robot collaborative assembly station that maximizes human comfort and acceptance while still supporting the needs of production. To accomplish this, the perspective of a company who wants to implement a collaborative robot was taken. This was to exemplify the importance of involving the operator in the process of implementing a HRC workstation. The operators should be treated like customers since the success of HRC heavily depends on the operator's acceptance and comfort. The operators have the ability to provide the company with recommendations and contribute to ensuring efficient HRC. Through the use of Lean Six Sigma tools such as Voice of Customer (VOC), Affinity Diagrams, Critical to Quality (CTQ), Kano, and Quality Function Deployment (QFD). Any company can take the information provided by their operators and turn it into valuable design requirements. The steps to recreate the process used in this thesis are listed below:

1. Conduct Background Research
2. Conduct Surveys and Interviews
3. Determine Operator Requirements
4. Determine Design Requirements
5. Determine Subsystem Requirements
6. Apply the Requirements

The use of cobots helps to provide a place for humans in the digital world of manufacturing, the only thing some companies lack is the guidance to implement them correctly. The process, tools and design requirements generated in this thesis should allow for proper implementation of cobots. It is important that companies get their operators

involved when the company is planning to introduce collaborative robots. Operators really appreciate being interviewed because it makes them feel valued and seen as experts for the working routines in which the robot would be integrated [65]. Furthermore, operators are much more likely to accept a system if they are personally involved [50].

It has been proven that after interacting with robots the participants began to see the robots as less of a threat to their jobs [52]. The positive experience with robots had a positive effect on their attitudes toward collaborative robots. This implies that the introduction of human-robot solutions should be preceded by a chance for the operator to acquire positive experiences with a robot. Many of the participants from the interview expressed the same desire to gain experience working with the robot. Perhaps before implementing the workstation created by the design requirements a company could give employees training and exposure. A good thing to do would be to measure acceptance before implementation. If it is low, then bring in some robots and let the employees test them out. Then measure the acceptance again. There should be an improvement and that is how the company will know the robots are ready to be installed and accepted by the workers.

Based on the research conducted in this thesis, perception plays a huge role in human factors and acceptance. For example, the perceived safety of working with the robot, the perceived reliability of the robot, and the perceived fluency of the interaction based on the robot's motion and pick-up speed can impact different operators in different ways [57]. This is why it is important to create a personalized experience and consider the preferences of the worker. The use of the survey and interview tools allow for a company

to determine what preferences their operators would have for controlling the robot. This makes it possible to design a workstation to incorporate the preferences that would benefit the majority of the operators.

### **Contribution**

The contributions from this thesis include the development of an implementation process that will ensure the involvement of the operator and tend to their need for comfort and acceptance in the system. The survey and interview tools can be used to determine what the most important features are since it may not be possible to develop a system with the ability to meet every unique need of each operator. Lastly, the design requirements generated can be used to guide the design of any collaborative workstation.

### **Limitations**

The limitations in this thesis include the inability to test this approach on a truly collaborative workstation due to the short comings of the industry and preferences towards non-collaborative setups for HRC. The small sample size for the surveys and interviews were also a limitation. Fortunately, due to the diversity in participants five interviews were enough to capture a good range of responses. The subjectivity of the QFD was another limitation. It is possible that someone else could go through this process and come up with different rankings and priorities for the requirements.

### **Future Work**

Some areas to explore in the future would include determining the ideal balance between preferences and the demands of production, and the creation of an interactive

profile that allows operator's to set their preferences and learn more about the capabilities of the robot. While this idea was intriguing to participants from the interviews conducted in Chapter three there are some valid concerns with impact on production and identifying the appropriate preferences for operators to have control over. One avenue for future research would be to conduct experiments to determine the ideal restrictions and preferences that would bring comfort and acceptance to operators without hindering production.

Another option for future work would be to take the six-step process conducted in this thesis and apply it to another real-world industry project that can reach the implementation phase. Once the six-step process is completed and the workstation has been implemented the operator's feelings and opinions should be documented. The efficiency of the HRC workstation and the ability to meet demands of production would need to be documented as well. Then once the operators have had some time to adapt to the workstation their feelings and opinions should be documented again. Gathering this information will make it possible to compare the change of acceptance and comfort overtime. Furthermore, the results could be compared with Wurhofer et al.'s findings. Unfortunately, the operators from Wurhofer et al.'s findings were not happy with the implementation process. If majority of the operator's feelings and opinions are positive before, during and after the six-step process then it will be proven as a good approach to implementing HRC.

## APPENDICES

## Default Question Block

Thank you for taking the time to complete this survey! The results of this survey will help with the completion of a Master's Thesis. The purpose of this survey is to explore how engineers can make your experience working with robots better. It may be possible to customize robots to match each employee's preferences. Imagine that you work with a robot that changes its behavior to match your preferences. Maybe your robot acts differently during a different shift. Just like elementary school kids act different with their parents vs teachers vs best friends vs grandparents who live to spoil them. Before starting you will read an informational letter required by the ethics committee.

Information about Being in a Research Study  
Clemson University

## Personalized Human-Robot Collaboration

### KEY INFORMATION ABOUT THE RESEARCH STUDY

Dr. Laine Mears is inviting you to volunteer for a research study. Dr. Laine Mears is a Professor at Clemson University conducting the study with Jassmyn McQuillen.

**Study Purpose:** The purpose of this survey is to explore how engineers can make your experience working with robots better. We believe it will be possible to customize robots to match each employee's preferences and would like to know what you think about this idea.

**Voluntary Consent:** Participation is voluntary, and the only alternative is to not participate. You will not be punished in any way if you decide not to be in the study or to stop taking part in the study.

**Activities and Procedures:** Your part in the study will be to complete a survey that will ask you for your background information, determine your current opinion of robots and will end with questions about what you dream about in a personalized robot that acts exactly as you want it to, in order to make your job easier and more satisfying. Upon completion of the survey if you choose to volunteer for a follow up interview then you will be asked for more details based on your responses. Not all participants will be asked to do a follow up interview.



**Participation Time:** It will take you up to 1 hour to be in this study. This includes 15 mins for the survey and 45 mins if you volunteer to do a follow up interview.

**Risks and Discomforts:** We do not know of any risks or discomforts to you in this research study. However, we will do our best to make sure you are comfortable and that your time is used wisely.

**Possible Benefits:** You may not benefit directly from taking part in this study; however, you will have the opportunity to have a say in how operators would prefer to work with robots. This can help improve collaborative workstations in manufacturing.

## **EXCLUSION/INCLUSION REQUIREMENTS**

In order to be involved in this study you must have knowledge of the processes of an assembly line.

## **AUDIO/VIDEO RECORDING AND PHOTOGRAPHS**

If you volunteer to do an interview, then you will be audio recorded for the entirety of the session. This recording will not be shared publicly. It will be used to document your responses later. Once your responses are documented the recording will be deleted and any identifiers will be removed.

## **PROTECTION OF PRIVACY AND CONFIDENTIALITY**

The results of this study may be published in scientific journals, professional publications, or educational presentations.

Identifiable information collected during the study will be removed and the de-identified information could be used for future research studies or distributed to another investigator for future research studies without additional informed consent from the participants or legally authorized representative.

## **CONTACT INFORMATION**

If you have any questions or concerns about your rights in this research study, please contact the Clemson University Office of Research Compliance (ORC) at 864-656-0636 or [irb@clemson.edu](mailto:irb@clemson.edu). If you are outside of the Upstate South Carolina area, please use the ORC's toll-free number, 866-297-3071. The Clemson

IRB will not be able to answer some study-specific questions. However, you may contact the Clemson IRB if the research staff cannot be reached or if you wish to speak with someone other than the research staff.

If you have any study related questions or if any problems arise, please contact Jassmyn McQuillen at Clemson University at 803-847-0366 or [jassmym@g.clemson.edu](mailto:jassmym@g.clemson.edu)

## CONSENT

By participating in the study, you indicate that you have read the information written above, been allowed to ask any questions, and you are voluntarily choosing to take part in this research. You do not give up any legal rights by taking part in this research study.

Would you like to participate in this survey

- ☐ No  
☐ Yes

You will be asked a series of questions. The survey will begin with background information before questions about your opinions. The survey will end with questions about what you dream about in a personalized robot that acts exactly as you want it to, in order to make your job easier and more satisfying.

Upon completion of this survey you may wish to volunteer for a follow-up interview where you will be asked follow-up questions and examples, to ensure your thoughts, ideas and beliefs are properly documented.

What organization do you work for?

How young are you?

- ☐ Under 18  
☐ 18 - 24  
☐ 25 - 34  
☐ 35 - 44  
☐ 45 - 54

- ☐ 55 - 64
- ☐ 65 - 74
- ☐ 75 or older

Answer the following questions with a yes or no.

	Yes	No	I don't know
Do you use a smartphone (iPhone or android)?	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Do you use a tablet or laptop at home weekly?	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Do you use a Roomba or robotic floor cleaning system at home?	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Do you use the features of a smart TV on a regular basis?	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Do you use an Alexa or Google Home at your home?	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Do you want a fully autonomous vehicle someday?	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Of the following what was your favorite required class in high school?

- ☐ Math
- ☐ English
- ☐ Science
- ☐ History

How many years have you worked at your current company?

- ☐ Less than one year
- ☐ 1-2 years
- ☐ 2-4 years
- ☐ 4-6 years
- ☐ More than 6 years

What is your current position?

How many years have you worked in this position?

- ☐ Less than one year
- ☐ 1-2 years

- ☐ 2-4 years
- ☐ 4-6 years
- ☐ More than 6 years

Have you ever worked with a robot at a Manufacturing facility?

- ☐ No
- ☐ Yes

Which of these statements describe how you and your robot work or worked together.

- ☐ My robot and I are located within the same workstation or workspace at the same time. We each have completely different assignments. (You are both using a drill to screw in bolts to two separate parts)
- ☐ My robot and I are located within the same workstation or workspace at the same time. We are working on the same assignment separately. (Your robot passes you the drill and components necessary to screw bolts into a part.)
- ☐ My robot and I are located within the same workstation or workspace at the same time. We are working on the same assignment and we make physical contact with one another. (Your robot has a drill attachment and screws in the bolts while you guide it or your robot holds and rotates the part for you while you use a drill to screw in the bolts.)
- ☐  Other

How often do or did you work with your robot?

- ☐ Every day
- ☐ A couple times a week
- ☐ Rarely
- ☐  Other

How many years have or had you worked with your robot?

- ☐ Less than a year
- ☐ 1-2 years
- ☐ 2-4 years
- ☐ 4-6 years
- ☐ More than 6 years

If you have worked at a company during the introduction of robots into the assembly process, how was the robot initially introduced to you? For example, did you walk in one day and it was installed onto the line or did the company let you know ahead of time that a robot would be added to the line?

- ☐ The company let us know ahead of time that they were considering installing a robot
- ☐ I walked in one day and the robot was installed onto the line
- ☐ Robots were already in use when I started working
- ☐  Other

For the following questions, please select the answer that best describes how you feel. If you have not worked with a robot answer the questions based on how you think you would feel.

Answer the following questions about your relationship with robots.

	No	Yes
I view working with a robot as a threat.	<input type="radio"/>	<input type="radio"/>
I view working with a robot as an opportunity.	<input type="radio"/>	<input type="radio"/>
I believe that robots are reliable.	<input type="radio"/>	<input type="radio"/>
I feel safe while working with a robot.	<input type="radio"/>	<input type="radio"/>

I enjoy working with a robot.

- ☐ No
- ☐ Yes
- ☐  Other

Working with a robot \_\_\_\_ my efficiency.

- ☐ Decreases
- ☐ Increases
- ☐  Other

I feel like a valuable employee while working with a robot.

- ☐ No

- ☐ Yes
- ☐  Other

For the following questions, please select the answer that best describes how you feel ranging from never to always. If you have not worked with a robot answer the questions based on how you think you would feel.

While working with a robot I feel challenged in a good way.

- ☐ Never
- ☐ Sometimes
- ☐ About half the time
- ☐ Most of the time
- ☐ Always

While working with a robot I feel happy.

- ☐ Never
- ☐ Sometimes
- ☐ About half the time
- ☐ Most of the time
- ☐ Always

While working with a robot I feel excitement.

- ☐ Never
- ☐ Sometimes
- ☐ About half the time
- ☐ Most of the time
- ☐ Always

While working with a robot I feel productive.

- ☐ Never
- ☐ Sometimes
- ☐ About half the time
- ☐ Most of the time
- ☐ Always

For the following questions, please select the answer that best describes how you feel ranging from never to always. If you have not worked with a robot answer the questions based on how you think you would feel.

While working with a robot I feel helpless.

- ☐ Never
- ☐ Sometimes
- ☐ About half the time
- ☐ Most of the time
- ☐ Always

While working with a robot I feel impatient

- ☐ Never
- ☐ Sometimes
- ☐ About half the time
- ☐ Most of the time
- ☐ Always

While working with a robot I feel frustrated.

- ☐ Never
- ☐ Sometimes
- ☐ About half the time
- ☐ Most of the time
- ☐ Always

While working with a robot I feel anxious.

- ☐ Never
- ☐ Sometimes
- ☐ About half the time
- ☐ Most of the time
- ☐ Always

Do you believe that a robot is there to support you?

- ☐ No
- ☐ Yes

Do you believe that a robot is there to assist you?

- ☐ No
- ☐ Yes

What would help create a team-like experience between you and your robot?

For the following questions, please select the answer that best describes how you would feel about your future experience with your robot.

If my robot changes its behavior to match my preferred method of working, I would see this as a \_\_\_\_.

- ☐ Threat
- ☐ Opportunity

While at work, I would feel \_\_\_\_\_ wearing a device like a Fitbit that knows who I am so my robot can identify me and my work preferences.

- ☐ Extremely uncomfortable
- ☐ Somewhat uncomfortable
- ☐ Neither comfortable nor uncomfortable
- ☐ Somewhat comfortable
- ☐ Extremely comfortable

Is there anything else you would want the device to do to help you work with the robot?

How would you prefer the robot to keep track of your preferences?



Would you prefer your robot to work at your pace?

- ☐ No
- ☐ Yes

For the following items, please select the answer that best describes you, ranging from strongly disagree to strongly agree.

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
I would prefer to receive immediate feedback even if it interrupts what I am doing.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I would prefer to receive feedback after completing a task.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I would prefer to receive feedback I can hear (my robot speaking to me).	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I would prefer to receive feedback I can see (using a monitor or lights, green for correct / red for incorrect).	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I would prefer to receive feedback I can feel (vibration from a device like a Fitbit).	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

For the following items, please select the answer that best describes you, ranging from strongly disagree to strongly agree.

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
I would prefer to communicate using body language (gestures, facial expressions).	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I would prefer to communicate by talking (giving instructions).	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
I would prefer to communicate by demonstration (showing my robot what I want it to do).	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I would prefer my robot (team member) to follow my lead.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I would prefer my robot (team member) to give me suggestions.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

For the following items, please select the answer that best describes you, ranging from strongly disagree to strongly agree.

	Strongly disagree	Somewhat disagree	Neither agree nor disagree	Somewhat agree	Strongly agree
I would prefer to work in close proximity with my robot.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
I would prefer my robot to be further away from me.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
When working in a team, I would prefer to split up tasks and work separately.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
When working in a team, I would prefer to work on tasks together.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

If you could talk to the engineers who build the robots, what would you ask the engineers to build into the robot just for you?

How could working with a robot be more enjoyable?

How much control would you like to have over your robot?

- ☐ None at all
- ☐ A little
- ☐ A moderate amount
- ☐ A lot
- ☐ A great deal

When working with your robot, what feature would be most important to you? Drag the options in order to rank them from most important (1) to least important (6). Feel free to add another option in the text box next to Other.

Controlling how fast or slow your robot moves

Controlling how you and your robot communicate with each other

Controlling how you and your robot interact (working on tasks together or separately)

Controlling how close your robot is to you when it is not moving

Controlling how close your robot is to you when it is moving

Other

Would you like to volunteer for a follow up interview?

- ☐ No
- ☐ Yes

What is your first name?

What is your last name?

Please provide your email and/or phone number below.

Thank you for your responses! Your help is greatly appreciated!

Powered by Qualtrics

1. So, tell me a little about yourself, what's your current position, and professional background, how long have you worked here and your age?
2. Have you ever worked with robots? In what capacity?
3. What is your view on working with robots in a collaboration workstation setting without fences, where the robot may be handing you parts or holding things for you or helping you put something together?
4. Does the idea of working with robots make you anxious, why?
5. When you have concerns about working with robots are you worried about the robot itself or the way that it is implemented?
6. Would you feel anxious if they were implemented for the sole purpose of assisting you?
7. What would make you feel challenged, happy, excited, valuable, and productive while working with a robot?
8. What would make you feel more comfortable and accepting of working with a robot?
9. Would having more control make you feel more comfortable and accepting?
10. What aspects of a collaborative robot would you like to be able to control and why?
11. Would you like to control the following features, if so which would be the most important to you and why?  
Is there anything missing?
  - a. Moving proximity
  - b. Stationary proximity
  - c. Speed
  - d. Communication style
  - e. Working style
12. What would be the best communication style for you and your robot?
13. What would be the best working style for you and your robot?
14. What requirements would you have for working with a robot?
15. From this list of requirements what's the most important to you and why? Is anything missing?
  - a. That the robot is dependable
  - b. That the robot is controllable
  - c. That the robot is helpful
  - d. That the robot includes extra features such as heart monitoring
  - e. That the robot teachable
  - f. That the robot is safe
  - g. Value-adding
  - h. Feasible communication
  - i. Easy to fix
16. What features would help meet your requirements?
17. Would this list of features meet your requirements? Is anything missing?
  - a. Poke Yoke Systems
  - b. Ability to work around robot
  - c. Good task allocation
  - d. User controlled preferences
  - e. Wearable devices
  - f. Entertainment System
  - g. Proof of improvement
  - h. Intentional Implementation
  - i. Good robot placement
  - j. Appropriate sensors
  - k. Communication system
  - l. Appropriate end effectors
  - m. Learning System
18. What should we as engineers focus our attention on the most from this list of requirements and features?
19. How would you feel about a robot that adapts to your preferences over time?

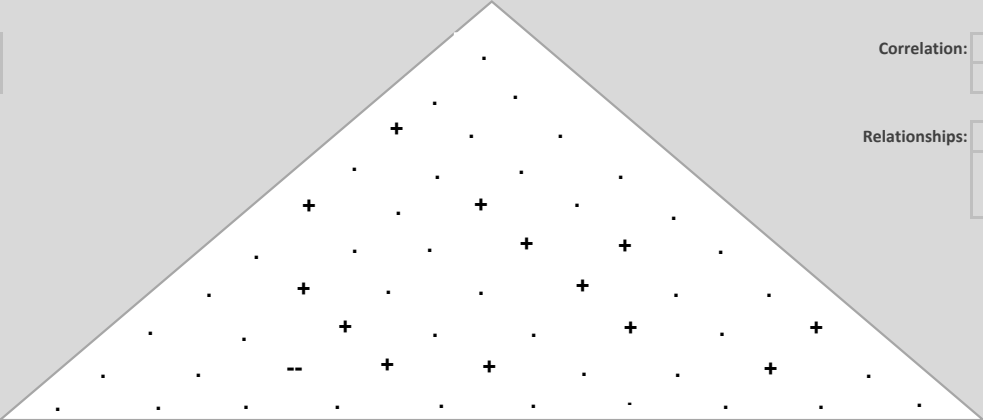
20. How would you feel about an interactive profile that allows you to let the robot know your preferences and provide you with information about the robot's capabilities?
  - a. Do you think there are any benefits or disadvantages to this?
21. Which would you prefer? Why?
22. Do you have any additional comments or suggestions?
23. Imagine this. Your boss tells you; you will be placed at a new workstation with a collaborative robot. There will be no fence around the robot, but the proper safety measures will be put in place. The product that this workstation would be producing are kitting orders. These kits would contain material such as screws, bolts, nuts, and gussets that can be used with aluminum extrusion to build things. Each kit contains up to 6 different components and each order can contain up to 300 identical kits. There are 38 unique components and 26 unique kits. Components must be picked and then placed into a bag that needs to be labeled and placed into a box for shipping. How would you prefer to work with the robot in this setting?

# Quality Function Deployment

Project Title: [HRC Workstation](#)  
Project Leader: [Jassmyn McQuillen](#)

Correlation:	+	.	--
	Positive	No correlation	Negative

Relationships:	9	3	1	
	Strong	Moderate	Weak	None



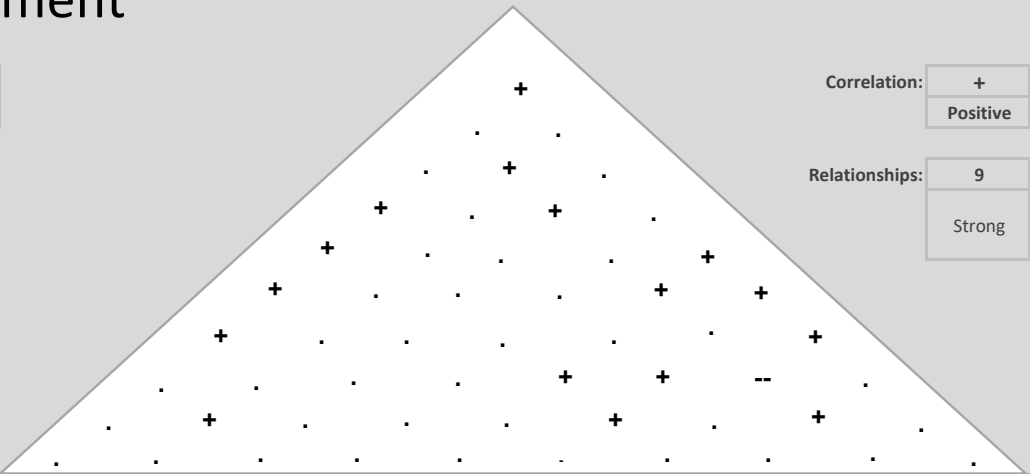
1: low, 5: high		Functional Requirements (How) →	Quality Control	Ability to work around robot	Good task allocation	User controlled preferences	User Engagement	Proof of improvement	Efficient Workstation Layout	Information flow	Efficient human-robot interface	Ability to handle variation	Weighted Score
Customer importance rating		Customer Requirements - (What) ↓											
1	5	Dependable	9	3	9				3	3	9	9	225
2	5	Safe		3	3				3	9	3		105
3	5	Value-adding	3		9	1	3	9	9			9	215
4	4	Controllable				9	9			3	3		96
5	4	Helpful	3		9	1	9	3	3	1	1	9	156
6	3	Easy communication				3	9		1	9	9		93
7	2	Teachable					3			3	9	1	32
8	2	Easy to fix					1		3	3	3		20
9	1	Enjoyable			1	9	9	3		1	3		26
		Technical importance score	72	30	142	63	131	60	96	116	130	128	968
		Importance %	7%	3%	15%	7%	14%	6%	10%	12%	13%	13%	100%
		Priorities rank	7	10	1	8	2	9	6	5	3	4	

# Quality Function Deployment

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Project Leader: Jassmyn McQuillen

Correlation:	+	.	--
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Relationships:	9	3	1	
	Strong	Moderate	Weak	None



Robot System Requirements (How) →		Safe	Vision Capabilities	Grasping Capabilities	Provide Feedback	Receive Information	Easy to use	Controllable	Teachable	Adaptable	Interruptible	Weighted Score
Design Requirements - (What) ↓												
1	5	Information flow	9	9								90
2	4	Quality		9						9		72
3	4	Good task allocation		3	9	1	1	9	1	3	9	144
4	4	Ability to handle variation		9	9		3	1		9	9	160
5	3	Ability to work around robot	3								3	45
6	3	User controlled preferences				9	1	9		9		84
7	3	Proof of Improvement			3							9
8	3	Efficient Workstation Layout								9		27
9	1	User Engagement	9			9	9	9	3	1	3	52
10	1	Efficient human-robot interface			9	9	9	9	9		9	54
Technical importance score		63	93	108	31	61	61	49	60	172	39	737
Importance %		9%	13%	15%	4%	8%	8%	7%	8%	23%	5%	100%
Priorities rank		4	3	2	10	5	5	8	7	1	9	

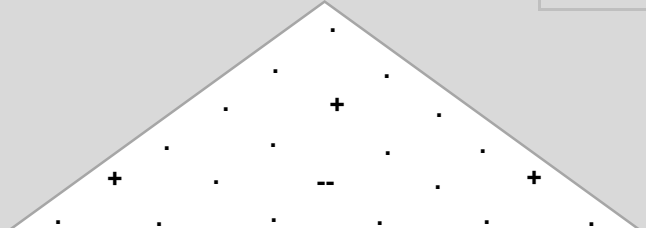


# Quality Function Deployment

Project Title: [HRC Workstation](#)  
Project Leader: [Jassmyn McQuillen](#)

Correlation:	+	.	--
	Positive	No correlation	Negative

Relationships:	9	3	1	
	Strong	Moderate	Weak	None

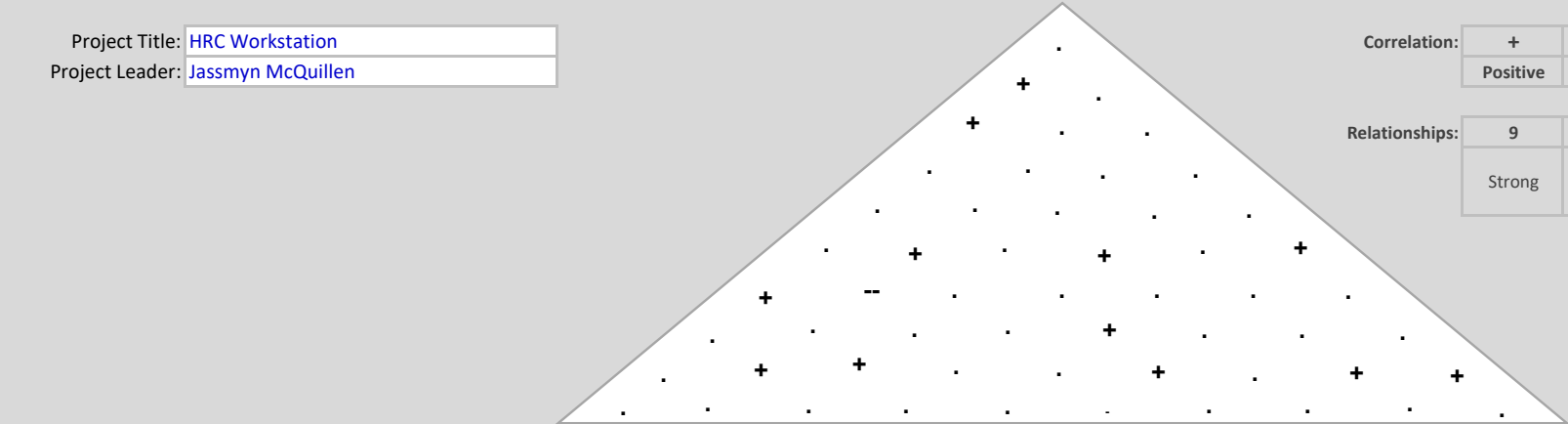
									
		<b>Validation System Requirements (How)</b> →							
		<b>Design Requirements - (What)</b> ↓							
1: low, 5: high									
importance rating		Vision Capabilities	Notification System	Prevention Procedures	Correction Procedures	Error Tracking System	Information Storage	Weighted Score	
1	5	Information flow	3	9			3	75	
2	4	Quality	9	3	9		3	132	
3	4	Good task allocation			3	3		24	
4	4	Ability to handle variation	9		3	3	9	96	
5	3	Ability to work around robot						0	
6	3	User controlled preferences		9				27	
7	3	Proof of Improvement	1	3		9		39	
8	3	Efficient Workstation Layout						0	
9	1	User Engagement		3		9		12	
10	1	Efficient human-robot interface		9				9	
		Technical importance score	90	105	60	24	48	87	414
		Importance %	22%	25%	14%	6%	12%	21%	100%
		Priorities rank	2	1	4	6	5	3	

# Quality Function Deployment

Project Title: HRC Workstation  
Project Leader: Jassmyn McQuillen

Correlation:	+	.	--
	Positive	No correlation	Negative

Relationships:	9	3	1	
	Strong	Moderate	Weak	None



1: low, 5: high		Structure System Requirements (How) →	Strength	Adaptable	Ergonomic	Safe	Organized	Accessible	Storage Capabilities	Stable	Longevity	Easy to Maintain	Weighted Score
		Design Requirements - (What) ↓											
1	5	Information flow					3						15
2	4	Quality	3				9			3			60
3	4	Good task allocation	3	3			3	3	3	3			72
4	4	Ability to handle variation		9									36
5	3	Ability to work around robot				9		9					54
6	3	User controlled preferences		3									9
7	3	Proof of Improvement											0
8	3	Efficient Workstation Layout		9	9		9	9	9		3	3	153
9	1	User Engagement			9		3	3					15
10	1	Efficient human-robot interface						3					3
Technical importance score			24	84	36	27	93	72	39	24	9	9	417
Importance %			6%	20%	9%	6%	22%	17%	9%	6%	2%	2%	100%
Priorities rank			7	2	5	6	1	3	4	7	9	9	

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